Comparison of Mechanical Properties ofAustenitic Ductile Cast Iron with Ferritic/Pearlitic Ductile Cast Iron

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by Shaik Shama

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under the supervision of

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We the below signed, after checking the dissertation mentioned above and the official record book (s) of the student, hereby state our approval of the dissertation submitted in partial fulfillment of the requirements of the degree of Master of technology in metallurgy and materials Engineering at National Institute of Technology Rourkela. We are satisfied with the volume, quality, correctness, and originality of the work.

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This is to certify that the work presented in this dissertation entitled " Comparison of mechanical properties of Austenitic Ductile Iron with Ferritic/Pearlitic ductile iron" by "*Shaik Shama"*, Roll Number 613MM3016, is a record of original research carried out by her under my supervision and guidance in partial fulfillment of the requirements of the degree of *Master of Technology* in *Metallurgical and Materials Engineering*. Neither this dissertation nor any part of it has been submitted for any degree or diploma to any institute or university in India or abroad.

....
Prof. Sudipta Sen

Dedication

I dedicate this to my Parents, Teachers and Fellow members without whom it was almost impossible for me to complete my thesis work

Declaration of Originality

I, *Shaik Shama*, Roll Number *613MM3016* hereby declare that this dissertation entitled "Comparison of mechanical properties of Austenitic Ductile Iron with Ferritic/Pearlitic " represents my original work carried out as a postgraduate student of NIT Rourkela and, to the best of my knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the section "Bibliography". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

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Abstract

Austenitic ductile iron belongs to the family of ductile iron which performs better properties than conventional ductile iron due to its soft matrix. Ductile iron (DI) has got enormous applications in different fields such as wind turbines, automotive components, spun pipe and fittings etc. As mechanical properties are primarily dependent on the matrix structure, different heat treatments are performed to the ductile iron to achieve required matrix. Alloying additions are made to stabilize the matrix structure at all the temperatures. In the present work, investigation has been conducted on mechanical properties of Ferritic/PearliticDuctile Iron and Austenitic Ductile Iron and comparison has been made by varying different heat treatments. Here, Austenitic phase is stabilized by adding Nickel as alloying element.

Stress relieving and austempering heat treatments are performed to Ferritic/Pearlitic Ductile Iron. Stress relieving treatment is carried out by heating the specimen to 600˚C, furnace cooling to 290˚C followed by air cooling to room temperature. Austempering treatment is carried out by heating the sample to 925˚C, quenching in salt solution maintained at 475˚C followed by air cooling to produce ausferritic matrix. Annealing treatment is done to Austenitic Ductile iron by heating the specimen to 1000˚C and then furnace cooled to room temperature to produce coarse grain structure. The microstructures of all the heat treated and as cast specimens are viewed under optical microscope and planes obtained for different phases are determined using X-Ray diffractometer. Morphological quantification like nodularity, nodule count are determined by following ASTM E2567-13a standard. Mechanical properties like tensile tests and hardness are conducted on (UTM) INSTRON-1995 and Vickers hardness tester respectively. Impact energies at room temperature and -20˚C are determined from Charpy impact tester. Fractures surfaces are viewed under scanning electron microscope in order to find out the type of fracture the specimen has undergone.

The results showed that the microstructures of as cast and stress relieved Ferritic/Pearlitic Ductile iron have 98% modularity with approximately83% ferrite as its matrix and 17% graphite, leading to higher amount of ductility and impact toughness. Whereas ADI consists of 93 % upper bainite and7% graphite nodules, resulting in higher hardness with considerable amount of ductility due to 95% nodularity. The redistribution of Carbon in austenite was shown 1.104%.

Austenitic Ductile iron consists of uniform 88 % austenitic matrix and 12% graphite nodules embedded in it with around 96 % nodularity. Austenitic Ductile Iron showed lower hardness and tensile strengths with higher elongations when compared to all the as cast and heat treated Ferritic/PearliticDuctile iron. As cast and stress relieved Ferritic/PearliticDuctile iron showed lower impact energies with quasi cleavage mode of fracture at room temperature but at -20˚C the values were decreased leading to slight brittleness in the material. Austempered Ductile iron showed brittle fracture at -20˚C from quasi cleavage fracture at room temperatures. Whereas austenitic ductile iron has quasi cleavage mode of fracture at both room temperatures and -20˚C showing no ductile to brittle transition has occurred.

Keywords*: *Austenitic Ductile Iron*;*Ferritic/Pearlitic Ductile Iron*; *heat treatments; mechanical properties*; *fracture surface

Contents

List of Figures

Literature Review

Experimental Details

Results and discussions

List of Tables

Chapter1
Introduction

1. Introduction

Austenitic cast iron is produced by taking a normal grey or ductile iron melt, controlling carbon and silicon levels and adding various alloys to produce a stable austenitic structure at ambient temperature. As nickel is the main alloying element, it is also called Ni Resist. It is cheaper than the equivalent alloyed steel particularly in terms of machining. Due to its high castability these are used for valves, pipe fittings, pumps, compressors and expanders. In present study material is developed for wind power applications.

1.1 Wind power

Wind power as an alternative to fossil fuels, is clean, widely distributed, produces no green house gas emission during operation and accommodates in little land. The force of the wind harnessed using wind turbines system is admirably suited for power generation. It is one of the lowest priced renewable energy technologies available today. Worldwide there are now 200000 wind turbines operating by the end of 2012. Wind production was around 4% of total worldwide electricity usage and growing rapidly [1]. As of 2014, Denmark has been generating 40% of electricity through wind energy and 83 countries around the world are using wind power to supply their electricity grids.

1.2 Onshore and offshore wind projects

Onshore wind is an inexpensive source of electricity and is cheaper than coal, fossil fuels plants or gas. But offshore wind is steadier and stronger than onshore wind but costlier with respect to maintenance. Wind speed is 20% higher than onshore. So offshore wind turbines have developed due to excellent offshore wind resource, in terms of wind power intensity and continuity [3]. A wind turbine installed in offshore can make higher power output and operate more hours each year compared with the same wind turbine installed onshore.

1.3 Materials used in wind turbine design

The materials used in wind turbine components should possess high strength, ease of manufacture, high impact toughness and corrosion resistance. Ductile iron has met more than the requirements for many of the components. Hubs and frames require mechanical properties that are similar to those of automotive safety parts. A combination of high toughness and resistance to failure at low temperatures are essential. Other parts require higher hardness and wear resistance, austempered ductile iron have been selected for these applications. Parts of rotor, nacelle and shell tower are made with steel [2-5]. Size of steel castings for large turbines mainly blade hub units is one of the challenges in manufacturing. Gear box, coolers are made with higher corrosive resistant materials. As ductile iron cheaper than steel, also having good combination of toughness and strength, studies were carried out to replace steel by ductile iron. DI over steel reduces weight of the component by over 10% [8].

1.4 Challenges in wind generation

1. Turbine noise is the main challenge in wind power generation which leads to noise pollution.

2. Offshore wind turbines installed in sea water have risks of structural corrosion under conditions of high wave, sea salt splashing and low temperatures.

3. Combination of water depth, the increasing wind tower heights and rotor blade diameters create loads complicating the foundation design and place a greater burden on the engineer to develop cost effective and innovative foundations and support structures.

These challenges led to the improvement of materials in wind turbines. To improve the corrosion and impact properties; Nickel is added to the ductile iron [6]. The mechanical properties of DI depend on the microstructure which contains spheroidal graphite and metallic matrix. The metallic matrix changes with the variation of different parameters such as cooling rate during solidification, chemical composition and solid state heat treatments. Ferrite, pearlite or combination of both can be obtained in as cast condition and martensite, pearlitic, bainitic (ausferritic) matrices can be attained by employing suitable heat treatments. The fracture process would be different in different materials which also depend on microstructure. In austempering heat treatment, component is heated to austenitizing temperature and holding there for sufficient time followed by quenching to get required bainitic matrix. The bainitic ferrite in austempered ductile iron is generated by the isothermal transformation of austenite in the bainitic transformation temperature range. Austempered ductile iron (ADI) has many advantages than forged steel. These advantages include 10% reduction in cost; have better scuffling resistance [7], less notch sensitivity than forged steels [8]. Due to these enormous advantages ADI replaces most of the steel components in automotive, aeronautical industry and earth movement applications like ripper tips and grader blades [21]. Even though Low nickel DI and ADI showed better results in improving corrosion resistance and impact toughness studies are still carrying out for a substitute which can work for longer years without changing the properties of the material. One problem with the ADI is during work hardening, this material will make machining more difficult due to tendency of retained austenite turning into martensite during machining.

So, Austenitic DI is chosen to examine mechanical properties and its fracture toughness to meet desired properties. Several studies have been reported on the distribution and concentration of alloying elements and the development of the microstructure on alloyed zone [52, 57]. As Nickel stabilizes Austenitic matrix even at room temperature austenitic ductile iron is potentially useful for higher temperatures. Austenitic ductile iron belongs to a family of ductile irons with microstructure consisting of graphite in the form of spheroids embedded in the austenitic matrix. Austenitic phase is stabilized at room temperature by adding alloying elements like nickel, chromium, copper, manganese. Increasing the nickel content resulted in higher tensile elongation at fracture without adversely affecting the strength or hardness. Copper is added to improve corrosion resistance. Manganese is added to improve cold toughness [63]. Austenitic cast iron has a range of properties which far outperform a normal ductile iron. It has scaling resistance, high resistance to heat, good thermal expansion characteristics, resistance to corrosion in sea water and alkaline liquids and atmospheres, good cold toughness and resistance to erosion. These offer numerous economic advantages compared to non corrosive heat resistant steel because the production process control is far simpler, the melting and casting temperature are lower. For application of high temperature about 675^0 C cast iron and steel passes through a critical range which frequently result in cracking and distortion of casting. This occurs due to volume change which is because of phase change of ferrite to austenitic. In austenitic or Ni resist Ductile Iron (DI), at all temperature doesn't have this transformation and contribute to high temperature application. Nickel content increases tensile strength and elongation at fracture without adversely affecting the yield strength and hardness [47].

In the present study, investigation is carried out on ductile iron by employing stress relieving and austempering heat treatment to low Ni DI and compare the properties with Austenitic ductile iron by correlating mechanical properties to microstructural changes. Effect of heat treatment on mechanical properties is also presented by comparing with as-cast mechanical properties of both the materials.

1.5 Objective of my present work

The main aim of present work is to

- Compare mechanical properties like tensile strength, hardness and impact toughness of Ferritic/Pearlitic Ductile iron with Austenitic Ductile Iron by subjecting them with different heat treatments
- A study on Impact toughness is done at room temperatures and subzero temperature (-20 ℃).

1.6 Thesis Outline

The thesis contains five chapters. The **1st Chapter, 'Introduction',** attempts to provide an insight of the work carried out and highlighting the background and motivation for the present work. The **2nd Chapter, 'Literature Review',** is dedicated to an extensive study of the work carried out by other investigators in the field. The work carried out by them has been referred wherever necessary to explain and support the experimental findings. The **3rd Chapter, 'Experimental Details',** explains the various experimental procedures adopted in the present investigation. The various instruments and the prescribed experimental norms have been explained in detail in this chapter. The **4th Chapter, 'Results & Discussions',** shows the various results in the form of Tables, graphs, SEM and optical images etc. The results have been explained and analysed in this chapter. Finally, on the basis of the experimental findings useful conclusions have been drawn which are listed in the **5thChapter, 'Conclusions'**.

Chapter 2
Literature Review

Literature review

2.1 Ductile iron and its importance

Cast iron due to its easy cast ability and numerous advantages where strength has the main priority, gained its importance in many industries. Cast irons are iron carbon alloys with carbon percent ranging from 2.11-6.67 [12] that can be illustrated from Fig 2.1. Microstructure consists of flake graphite embedded in ferrite/pearlite matrix. But flake graphite act like cracks in the iron matrix.

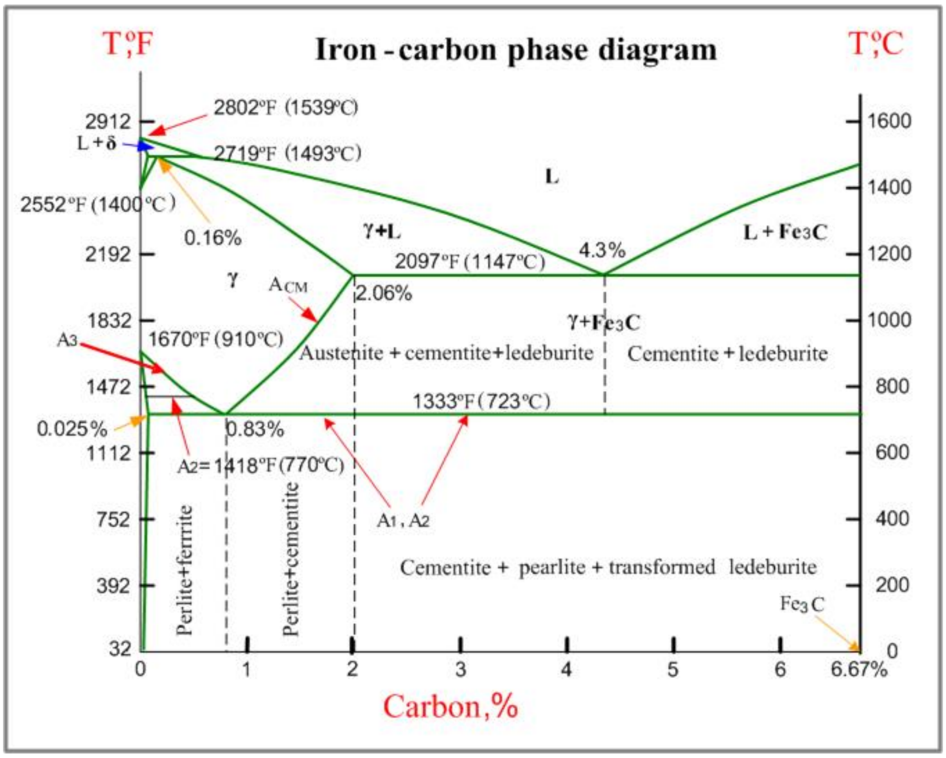


Fig 2.1: Iron Carbide Phase Diagram

With this failure, there lead to the invention of ductile iron which consists of nodular graphite that acts like crack arresters. In 1943, keith Dwight mills from international nickel company observed spheroidal graphite in iron matrix which was formed due to addition of magnesium to the liquid cast iron. Magnesium causes the graphite to precipitate in all directions as spheroidal nodules during solidification and also increases the super cooling of cast iron and consequent chilling [12]. The versatility and high performance of ductile iron at low cost are main reasons for their approach to aerospace and aeronautical industries. Ductile iron offers high ductility with elongations more than 18% and tensile strength exceeding 825MPa. The applications of ductile iron include trucks, agricultural tractors and oil well pumps. In wind power industry ductile iron is used for hubs and structural parts like machine frames [9]. This is also suitable for complex shapes and high loads. Depending on these performances there was a rapid increase in the production of ductile iron [16] shown in Table 2.1

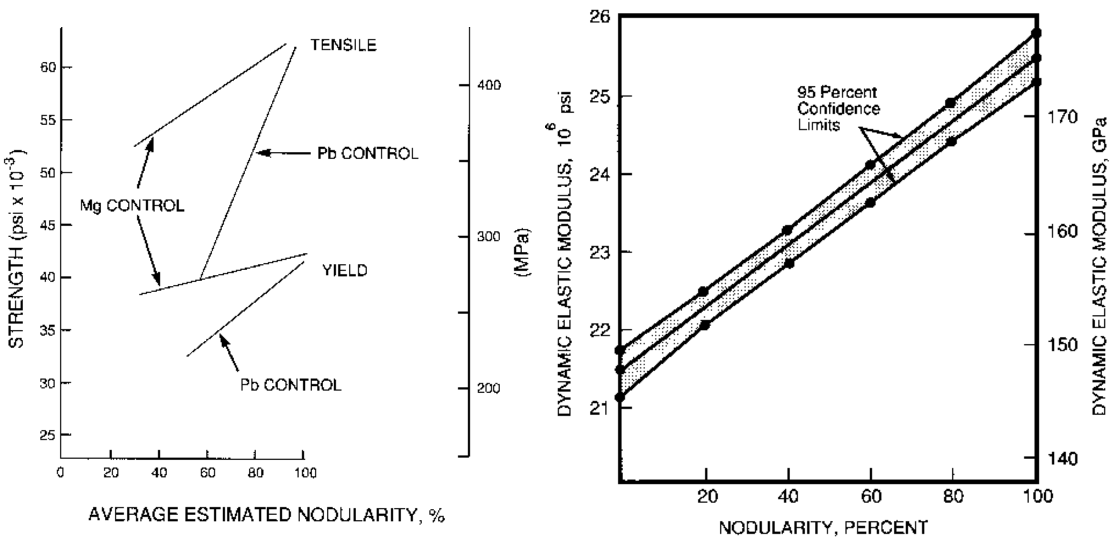
Table 2.1: Casting census of world casting production

Year	Total Casting Tonnage of Alloys (Millions of Metric Tons)			
	Grey Iron	Ductile Iron	Aluminum	Steel
2004	40.30	18.30	10.22	6.20
2005	40.60	19.30	11.50	8.90
2006	42.50	21.40	11.83	9.80
2007	44.65	22.50	12.60	9.81
2008	42.49	23.70	10.92	10.18
2009	37.68	19.75	10.40	8.90
2010	42.80	23.14	10.90	9.64
2011	45.90	24.40	12.80	9.87
2012	45.60	25.00	13.80	10.75
2013	47.60	24.75	14.90	10.73

Ductile iron is also known as nodular or spheroidal iron patented in 1948. It had a phenomenal increase in use as an engineering material in 1960's after intensive development work. This spheroidal graphite in DI has an unusual combination of properties when compared to individual flakes in cast iron. Nodules are obtained by adding a very small amount of magnesium to molten metal of proper combination. The magnesium reacts with the Sulphur and oxygen in molten iron and changes the graphite's form. High C, Si in DI provides advantages in the casting process and the formed spheroidal graphite have influence on the mechanical properties of the metal [18-20].

2.1.1 Effect of graphite shape

The nodularity plays a significant role in determining properties within DI family. Fig 2.2 (b) shows relationship between nodularity and dynamic elastic modulous. Fig 2.2 (a) shows relationship between nodularity and strength for ferritic irons in which nodularity has been changed by magnesium control and another by lead control [16]. Reduction in magnesium resulted in elongation in nodules. This resulted in 10% decrease in yeild strength and 15%decrease in tensile strength when nodularity reduced to 30%. Effect of nodularity shown in Fig 2.3 compared tensile properties at constant carbide levels with nodularities around 90, 70, and 40%. pearlitic iron is more sensitive to reduced nodularity. There is little loss in strength as the nodularity decreases to 70%, but as nodularity deteriorates further, strength decreases rapidly at low carbide levels of Ductile Iron.



(a) (b)

Fig 2.2: Effect of nodularity on (a) strength and (b) Dynamic elastic modulous

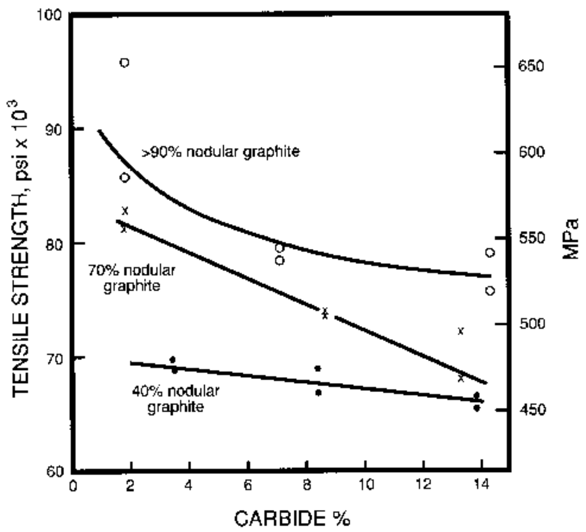


Fig 2.3: Effect of carbide on tensile strength

2.1.2 Effect of nodule count

It is expressed as the number of graphite/mm^2. It also influences the mechanical properties but not as directly as nodule shape. The optimum range of nodule count indicates good quality of DI where as excess count may result in degradation of properties. It does not affect tensile properties strongly but affects the microstructure. Increasing the nodule count decreases pearlite content, strength and increases elongation. It improves tensile strength, ductility and machinibility by reducing volume fraction of carbides. Increase in nodule count produces finer and more homogeneous structure. This refinement of matrix structure reduces segregation of harmful elements which produce intercellular carbides, pearlite. Also increase in nodule count results in decrease in nodule size that improves Tensile strength, fatigue and fracture properties [17].

2.1.3 Effect of Alloying Additions

Alloy additions are made to DI to assist in controlling the matrix structure of as cast or to provide response to heat treatments.

1. Aluminium: Small quantities of Al are added to reduce chill and effect deoxidations. But 0.01 to 0.2 % of Al causes pinhole porosity due to pick up of hydrogen.

2. Bismuth: 0.002% and 0.01 % is added to malleable iron melts (ladle additions). It enables higher silicon content in base metal without the formation of primary graphite.

3. Boron: it is a ladle addition to white cast iron for production of malleable iron castings. It neutralizes the graphite coarsening effect of bismuth and forms boride of chromium, thus suppressing the inhibiting effect of chromium on annealing cycle. 0.002% of boron and 0.008% of Bismuth together are added to malleable iron. Boron returned in internal scrap doesn’t interfere with mechanical properties but beneficial in neutralizing the effect of Nitrogen.

4. Chromium: it is a strong carbide stabilizer thus reducing the formation of free graphite and encouraging chill effect. 0.5-1.5 % of chromium is added as a ladle addition often in conjunction with nickel. Wear and heat resistant both are increasing with chromium. Carbon content of eutectic is reduced to 0.5 % for each 1 % of chromium. Addition of about 3% of Cr, the formation of graphite is suppressed and a white iron structure forms. Cr decreases the gamma region and raises critical transformation temperature. Gamma field is almost eliminated by 20 % Cr. Hardness increases to 6-10 pts Brinell for each 0.1% Cr.

5. Manganese: it is added to neutralise sulphur. It combines with sulphur and forms manganese sulphide and due low specific gravity it is separated by floatation from melt. It is best known for austenitic stabilizer in conjunction with Nickel.6-15 % manganese is added to non magnetic cast iron which has high electrical resistance.

6. Molybdenum: it is added to improve mechanical properties of high duty cast irons and for special compositions like acicular cast irons. It is a powerful promoter of pearlite. It favours in the formation of carbide/ austenite eutectic. It forms stable carbide and offsets the graphitising influence of about 0.35% Silicon.

7. Nickel: During solidification of eutectic the presence of nickel encourages approximately 1/3 rd that of silicon. 12.34% of Nickel stabilizes the austenitic matrix at room temperatures. Addition of 1-2 % Ni to grey irons composition raises the level of mechanical properties a little. It is due to the reduction in section sensitivity imparted by nickel. The hardness of this section decreases and that of heavy sections increases due to grain refinement.

2.2 Alloy cast irons

Alloying elements are added to cast irons to modify the mechanical properties and to

1. improve strength
2. improve toughness
3. achieve greater uniformity
4. decreased section sensitivity
5. achieve higher strength at elevated temperatures
6. improve hardenability of heat treated alloys
7. improve wear resistance
8. increase hardness and
9. improve low temperature impact properties.

2.3 Conventional Ductile Iron

Ductile iron provides best combination of overall properties mainly in the mechanical properties. The mechanical properties of DI depend on the microstructure which contains spheroidal graphite and metallic matrix (Fig 2.4). The metallic matrix changes with varying different parameters such as cooling rate during solidification, chemical composition and solid state heat treatments. Ferrite, pearlite or combination of both can be obtained in as cast condition and matrix like martensite, pearlite, bainite (ausferrite) can be attained by employing suitable heat treatments. In as cast condition microstructure consists of spherical graphite nodules embedded in pearlite/ ferrite matrix.

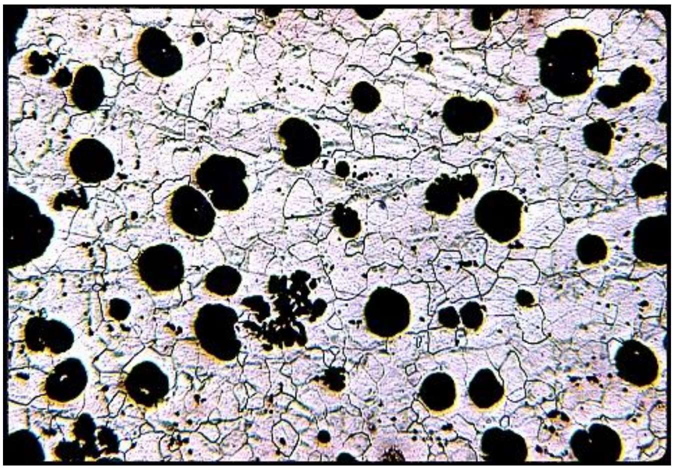


Fig 2.4: Microstructure of As cast DI

Ductile iron has similar engineering properties as steel engineering, and near-net shaped castings are replacing forgings, weldments, and steel castings in a variety of applications. Ductile iron is also available in continuously cast bars stock and can be a directly replaced for carbon steel bars in gear parts in the hydraulic, automotive, machine tool and other industries where strength along with toughness is the main criteria [9].

2.3.1 Heat treatments of ductile iron

The different heat treatment procedures usually adopted for ductile iron are

2.3.1.1 Stress relieving

This treatment is subjected to relieve internal stresses developed after solidification. Internal stress are relieved at temperature range of 510-625˚C. Holding time is one hour plus one hour per 25mm of section thickness. Then castings are furnace cooled to 290˚C followed by air cooling. This treatment reduces the hardness to some extent. Stress relieving of highly alloyed ductile iron is done by cooling from 595-650˚C.

2.3.1.2 Annealing

Annealing is done to improve ductility and machinibility. After annealing treatment the microstructure consists of graphite nodules surrounded by ferritic matrix. It is of three methods.

i. Heating the material to 900-950˚C and holding for one hour plus one hour per 25 mm section thickness. After holding the material is furnace cooled to 690˚C and hold at 5 hours plus one hour per 25 mm section thickness.

ii. Heating the material to 900-955˚C held for one hour and furnace cooled to 650˚C. Cooling rate between 790-650˚C should not exceed 20˚C per hour.

iii. Under conditions where impact strength is not of significance, the castings are heated to 700˚C and held there for 5 hours plus one hour per 25 mm section thickness followed by furnace cooling to 590˚C.

2.3.1.3 Normalizing

Normalizing is done to enhance the tensile properties of ductile iron. Casting is heated to 870-940˚C and soaking for one hour. Temperature and soaking time depends on composition mainly on silicon and chromium contents. Tempering is carried out after normalizing to relieve internal stresses that are developed during air cooling and to achieve required hardness. Tempering is a process where the casting is reheated to 510-620˚C and soaked for one hour after normalizing The microstructure of normalized specimen consists of fine pearlite and globular graphite. Alloy additions like nickel, molybdenum and additional manganese are added to develop fully pearlitic structure.

2.3.1.4 Hardening and tempering

In this treatment the castings are austenized at 845-925˚C followed by oil quenching to reduce stresses. Castings with simple shapes can be quenched in water and brine solutions. Castings with complex shapes are oil quenched in which oil is maintained at 80-100˚C to avoid quenching cracks. Hardening is followed by tempering to minimize quenching stresses by tempering in the range of 300-600˚C for one hour plus one hour per 25 mm section thickness.

2.3.2 Properties of conventional Ductile Iron

Ductile iron is essentially a family of materials with ample variety of properties that gives adequate results in distinct engineering requirements. Matrix structure is enhanced by using different heat treatments. Table 2.3 give you an idea about properties of ductile iron with different matrices [13-14]. Ductile iron has good mechanical properties above grey cast iron. Table 2.2 put on view about comparative properties of cast irons [15].

Table 2.2: Comparative properties of cast irons

Properties	Grey	CGI	Ductile
Tensile Strength(MPa)	250	450	750
Youngs Modulous(GPa)	105	145	160
Fatigue Resistance(MPa)	110	200	250
Heat Conductivity(W/mK)	48	37	28
Hardness (HB)	179-202	217-241	217-255
Relative Damping Capacity	1.0	0.35	0.22

Table 2.3: Properties of ductile iron with respective matrix structures

Matrix microstructure	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Brinell hardness
Ferrite	414	276	18	149-187
Ferrite +pearlite	448	310	12	170-207
Pearlite + ferrite	552	379	6	197-255
Pearlite	690	483	3	217-269
Tempered martensite	828	621	2	240-300

2.4 Ferritic Ductile Iron

Microstructure consists of graphite nodules surrounded by ferrite matrix (Fig 2.5). it provides iron good ductility and impact resistance with good tensile strengths and yield strengths equivalent to low carbon steels. These are produced in as cast conditions by using ferrite stabilizers but given annealing heat treatment to assure maximum ductility at low temperatures.

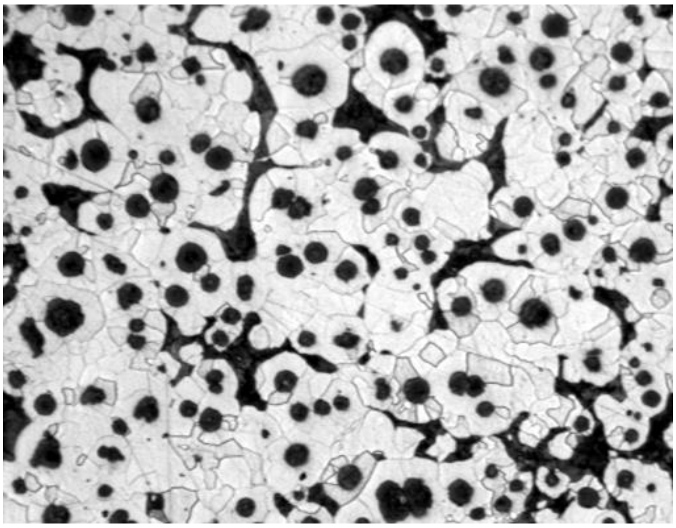


Fig 2.5: Microstructure of Ferritic Ductile Iron

2.5 Ferritic/ pearlitic Ductile Iron

These are the most common grades of ductile iron produced in as cast condition. Microstructure consists of graphite nodules embedded in ferritic/pearlitic matrix. These acquire intermediate properties between ferritic and perlitic grades with low production costs and good machinibility.

2.6 Pearlitic Ductile Iron

Microstructure consists of graphite nodules embedded in the pearlitic matrix(Fig 2.6). Pearlite results in good wear resistance, high strength, moderate impact resistant and ductility. Their machinibility and physical properties are superior to steels.

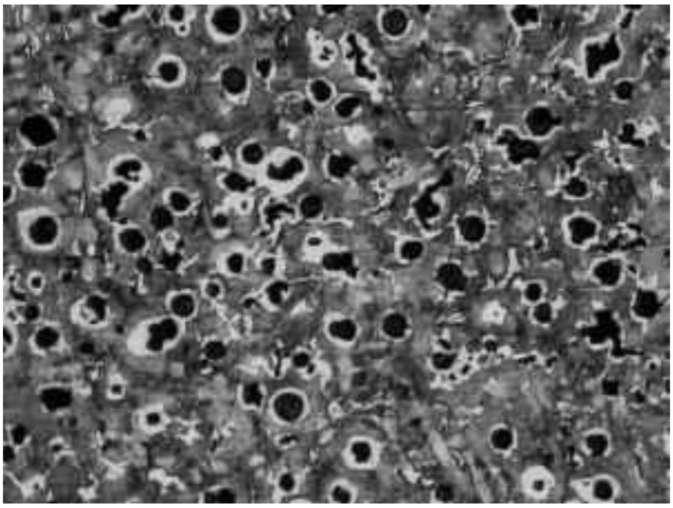


Fig 2.6: Microstructure of pearlitic Ductile Iron

2.7 Martensitic Ductile Iron

To prevent pearlite formation, sufficient alloy additions are added, and a quench-and-temper heat treatment produces martensitic ductile iron. The resultant tempered martensite matrix develops very high strength and wear resistance but with lower levels of ductility and toughness.Fig 2.7 shows different microstructures of martensite and tempered martensite.

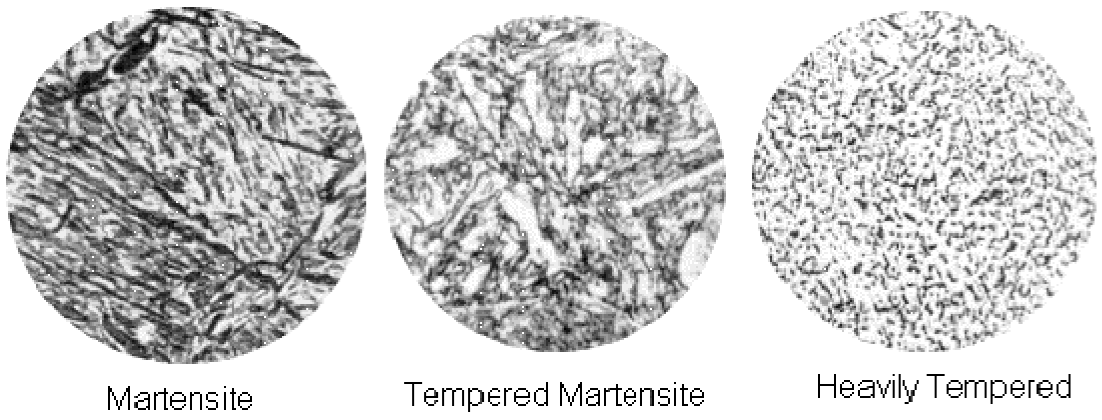


Fig 2.7: Microstructure of martensite and tempered martensite

2.8 Austempered ductile iron (ADI)

It is also known as ausferrite ductile iron and is a recent addition to the family of ductile iron. It is produced by treating a conventional ductile iron with austempering heat treatment. Even it has higher strengths when compared to the pearlitic or ferritic ductile iron still retains elongations and toughness. Fine grained acicular ferrite in ADI provides exceptional combination of high strength with good ductility and toughness.ADI has many advantages than forged steel. These advantages include 10% cheaper; have better scuffling resistance, less notch sensitive than forged steels.ADI gears run more quietly than equivalent steel gears. Due to these enormous advantages ADI replaces most of the steel components in automotive, aeronautical industry and earth movement applications like ripper tips and grader blades [8].

2.8.1 Formation of bainite

The heating of the samples to austenitizing temperatures in the range of 850-950°C,(Fig 2.9) transform as cast ferritic/pearlitic matrix into austenite and gets enriched with carbon from graphite nodules[23-27]. The microstructures that are formed at different temperatures are identified with the help of time temperature and transformation diagram shown in Fig 2.8

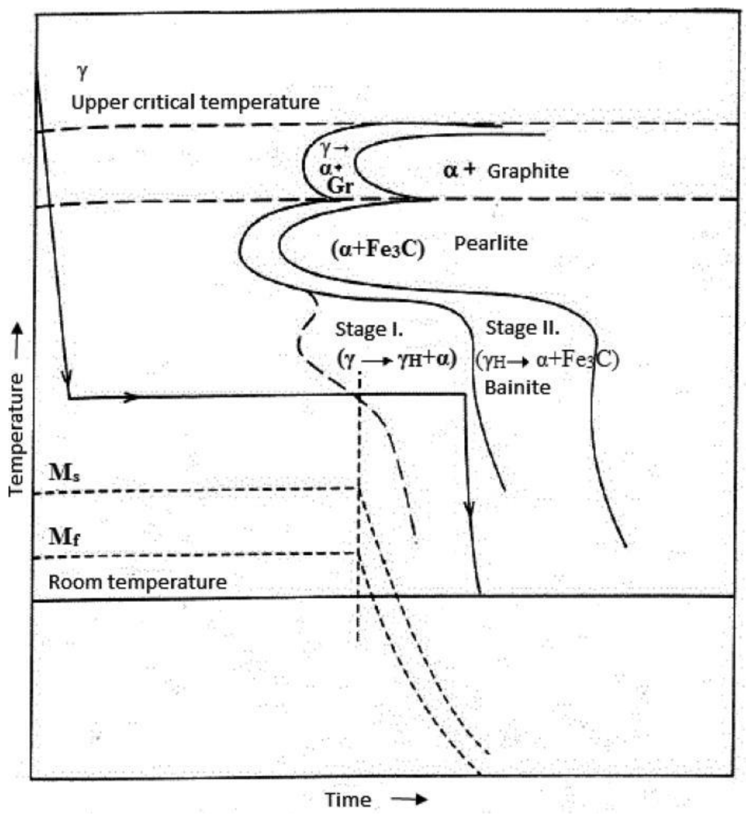


Fig 2.8: Time- Temperature-Transformation Diagram

Quenching to austempering temperatures (250-500°C) resulted in the growth of ferrite plates into the austenitic grains. As the solubility of carbon is low in ferrite and the presence of silicon in as cast iron controls the carbide precipitation, the excess carbon is redistributed into residual austenite surrounded by ferrite. Then austenite gets stabilized and samples are cooled to room temperature without forming martensite [23-24, 39]. There are two types of bainite structure. Upper bainite will form when samples are quenched in the range of 390°C-500°C.The upper bainite is coarser, feathery carbide free ferrite, distributed in high carbon retained austenite. Lower bainite forms at the quenching temperature range of 390-250°C [29-30].

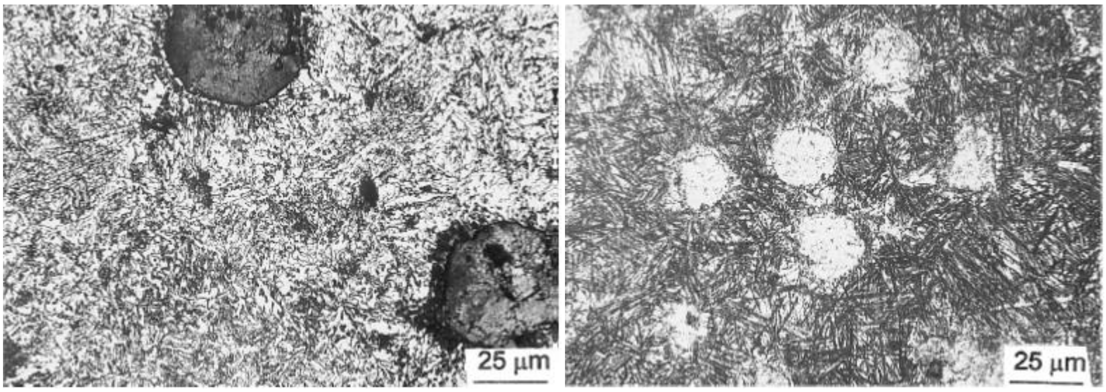


Fig 2.9: Microstructure of Austempered DI (a) upper bainitic (b) lower bainitic

The minimal incubation temperature at higher temperature is 450˚C and 360˚C at lower temperatures. The transformation from γ-phase to the bainitic α phase ceased after 1100s at 450˚C. Further holding leads to transformation of another phase starting after 3000s which corresponds to carbide precipitation that occur in DI after stabilizing two phase bainitic structure [24]. At lower temperatures (400˚ C, 350˚C,300˚C) this phenomenon was not found after holding for 7000-7200s as the incubation period is less in upper bainitic region and is equal to 180-225s.It is 300-600s at lower temperature range(390-250˚).

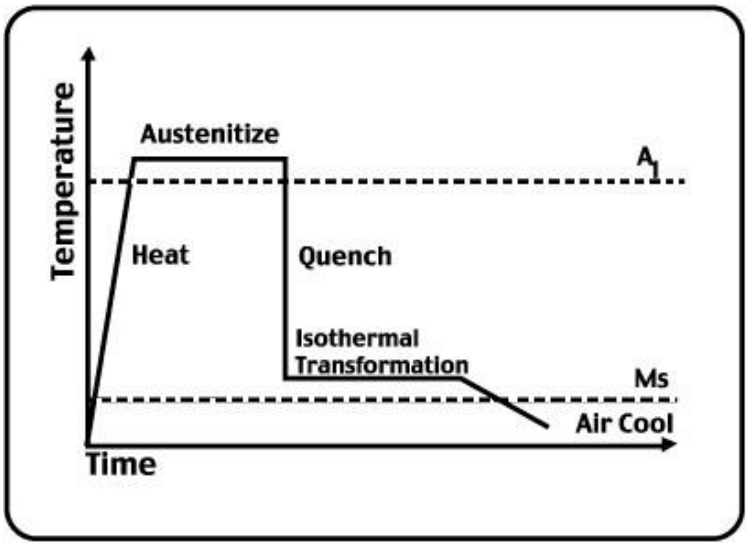


Fig 2.10: Cooling curve of Austempered Ductile Iron

The work of Kustuv and Taran [29] on ductile iron has shown that the volume fraction of austenite in the matrix in the isothermal transformation range between 400-250°C decreases (from 33 to 18%) with decrease of transformation temperature. The variation of carbon content and the c/a ratio in the bainitic α-phase against transformation temperature is given in Fig 2.11

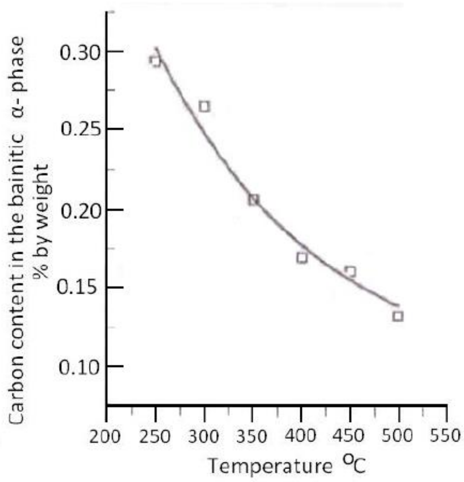


Fig 2.11: Variation of carbon content with transformation temperature

2.8.2 Mechanical properties of Austempered Ductile Iron

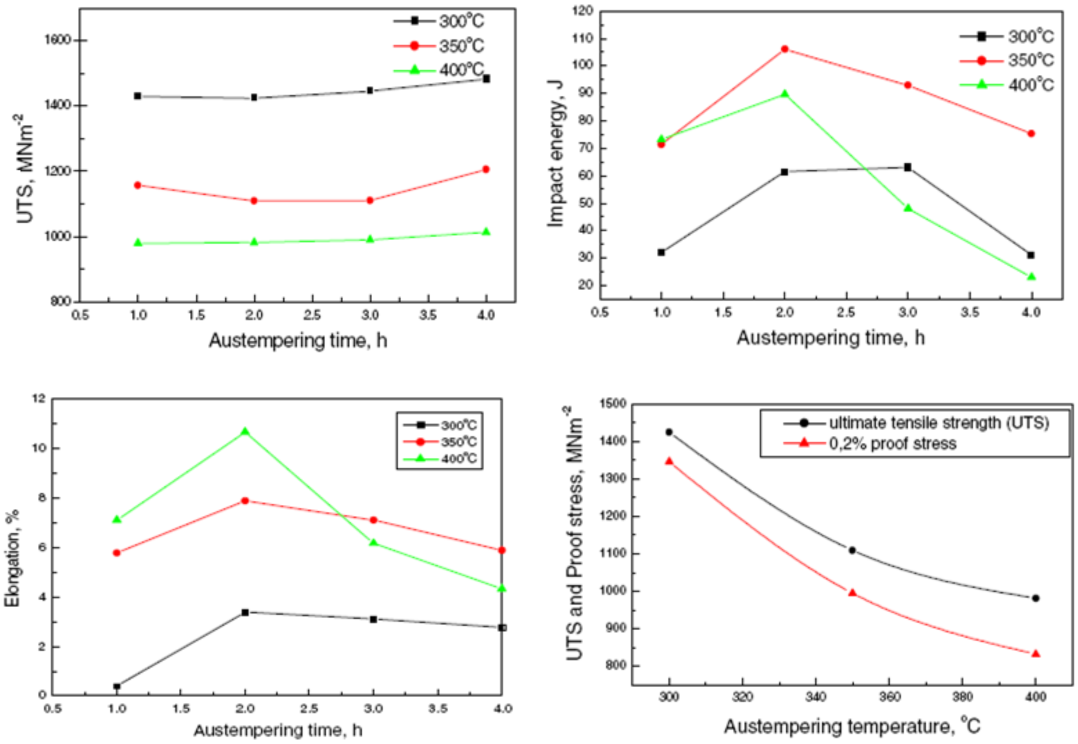
ADI has unique microstructure, a mixture of acicular ferrite and stable high carbon austenite. Fine acicular ferrite, austenite and carbon give ADI an excellent combination of strength, toughness and wear resistance and low temperature impact properties. Table shows the mechanical properties of ADI with different grades. Properties for different grades of austempered ductile iron [22] are shown in table 2.4.

Table 2.4: Mechanical properties of Austempered Ductile Iron

Sample Grade	Ultimate tensile Strength (MPa)	Yield strength (MPa)	Elongation (%)	Brinell hardness	Un notched impact energy (J)
1	900	650	9	269-341	100
2	1050	750	7	302-375	80
3	1200	850	4	341-441	60
4	1400	1100	2	388-477	35
5	600	1300	1	402-512	20

2.8.3 Effect of austempering variables on mechanical properties

Austempering time and temperature play important role in the resultant microstructures and in mechanical properties of ADI (Fig 2.12). The amount of high carbon retained austenite in the bainitic structure increases as the austempering time increases upto a certain time. Retained austenite plays an important role in the ductility and toughness of bainitic structure in ADI. And also by increasing temperature the amount of retained austenite is increased and carbon content of it is decreased. As a result austempering at high temperature results in more ductile structure with higher toughness when compared to austempering at low temperature. Increasing austempering time more than the optimum levels may result in the transformation of high carbon retained austenite to ferrite carbide which deteriorates the mechanical properties of ADI. Highest amount of hardness is achieved at low austempering time due to the amount of martensite that formed after austempering for longer time. By increasing austempering time UTS, yield strength, elongation and impact energy of ADI increases [28, 51].



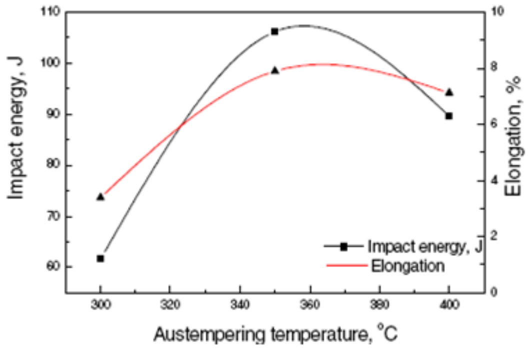


Fig 2.12: Effect of austempering parameters on Impact energy

2.8.4 Advantages of Austempered Ductile Iron

Development of ADI has provided the designer with a new group of ferrous metals which offer a combination of mechanical properties equivalent to cast nd forged steels [25]. The production costs are similar to those of as cast ductile irons. ADI also provides the designer with a wide range of properties, all produced by varying the heat treatment of the same castings, ranging from 10-15% elongation with 125 Ksi (870 MPa) tensile strength, to 250 ksi (1750 MPa) tensile strength with 1-3% elongation. Although initially hindered by lack of information on properties and successful applications, ADI has become an established alternative in many applications that were previously the exclusive domain of steel castings, forgings, weldments, powdered metals and aluminum forgings and castings.

2.9 Austenitic ductile iron

During solidification of eutectic the presence of nickel encourages approximately one third that of silicon. Additions of 1-2% Ni to the composition of grey iron have the effect of raising the level of mechanical properties. Ni content increases tensile strengths and elongations at fracture without affecting the yield strength or hardness. It is due to the reduction in section sensitivity imparted by Ni. The hardness of high sections increases due to the grain refinement. Addition 12-36% Ni to ductile iron stabilizes austenitic phase even at room temperatures. This austenitic stabilized ductile iron is called austenitic ductile iron also known as Ni resist DI. The microstructure consists of graphite nodules surrounded by austenitic matrix (Fig 2.13). It exhibits room temperature impact properties superior to those of ferritic/pearlitic grey cast iron. Austenitic DI has a range of properties which far outperform a normal grey or ductile iron. It has scaling resistance, good thermal expansion characteristics, high resistance to heat, good cold toughness, resistance to erosion, and resistance to corrosion in sea water and alkaline liquids [47]. Compared to non-corrosive heat resistant steel, Austenitic ductile iron offers numerous advantages in terms of production. These are Superior to grey cast irons particularly at low temperature. Some are nonmagnetic which have high electrical resistance and are widely used in handling sodium hydroxide and other strong caustic. It has high resistance to cracking and distortion above 65℃.These materials is superior at higher steam temperatures where resistance to growth and scaling is important. As nickel raises from 0-2 %, tensile stress,proof stress, and hardness are improved whilst toughness and ductility are not significantly impaired. The presence of Ni up to 2-5 % in ferritic Ni DI increases ultimate tensile and yield strength with negligible effect on elongation values [48-50].

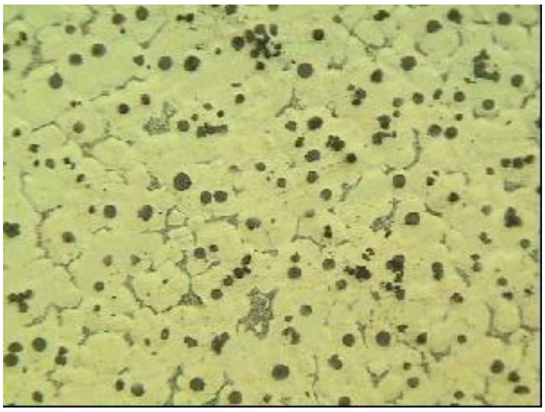


Fig 2.13: Microstructure of Austenitic Ductile Iron

Nabil Fatahalla et al. [46] studies on alloying elements to vary carbon equivalent of austenitic ductile iron shows that increase in carbon equivalent resulted in lower hardness , tensile strength and 0.2% proof stress where as ductility was enhanced.

Farjad Alabbasian et al. [58] Studies on effect of inoculation on microstructure show that the matrix consists of austenite and fine particles of $FeNi_3$, where Cr-rich carbide phase precipitates in grain boundary regions. These studies also show the enhancement of tensile strengths which were due to inoculation process by increasing graphite nodularity, nodule count and decreasing carbide formation.

2.9.1 Heat treatment of Austenitic DI

Complex austenitic castings should be mold-cooled to 315˚C before stress relieving treatment that should be done at 620-675˚C. Annealing softens and improves ductility by the decomposition and spheroidization of carbides. Annealing should be conducted at 965-1035˚C for 1to 5 hours depending on the size of the castings and degree of decomposition and spheroidization required. Soaking is followed by air cooling or furnace cooling to adopt desired elongations. When the material is to be used in applications at or above 480˚C, primarily castings are stabilized to minimize warpage and growth by holding at 870˚C for 2 hours, furnace cooling to 540˚C followed by air cooling to room temperature. To assure dimensional stability the castings are held at 870˚C for 2 hours and 1 hour per inch of section size, furnace cooled to 540˚C and cooled slowly to room temperature. After machining reheat the castings to 450-460˚C, soaking for 1 hour per inch of section to relieve machining stresses followed by furnace cooling below 260˚C [9, 52].

2.9.2 Properties of Austenitic cast irons

These provide special physical and mechanical properties (Table 2.5) which possesses high resistance to corrosion and heat. Impact resistance is governed by silicon content and temperature. Impact values fall below the normal values with increase in Si content and decrease in temperatures [53-55]. Further where silicon is controlled to 2.25% full ductility is maintained to a temperature of the order of -10˚C. If the same silicon is controlled to 1.4% the material can be ductile down to as low as -60˚C. With Austenitic cast irons full ductility can be maintained at even lower temperatures. Austenitic cast irons exhibit room temperature impact properties superior to ferritic/ pearlitic grey cast irons. Where graphite is in flake form, these are insufficient to render the material suitable for cryogenic applications. Spheroidal form of graphite made possible for requirements for temperatures as low as -196˚. The properties like tensile strength depend on the percentage of carbon equivalence. Required amount of tensile strength can be achieved by varying carbon equivalent [56]. Properties at sub zero temperatures depends on the form of the graphite present, the amount of eutectic carbide present and the stability of austenite. The impact strength depends on the temperatures where martensite begins to form, since martensite has an embrittling effect. Table shows the properties of austenitic ductile iron that vary with nickel percentages at room temperatures and 900˚C [69].

Maarof Mohd. Rashidi et al.[59] Studies on mechanical properties of modified Ni resist Ductile(DNR) iron show that tensile properties of modified DNR has lower value than unmodified DNR due to the less graphite in its microstructure, it also showed higher hardness of modified DNR that resulted due to the formation of carbide.

Table 2.5: Properties of Austenitic Ductile Iron

composition	Room temperature			900˚C		
Nickel (%)	Elongation (%)	YS (MPa)	UTS (MPa)	Elongation (%)	YS (MPa)	UTS (MPa)
20	24.6	241	521	25.7	49	67
25	20.8	240	481	28.3	43	63
30	25.0	226	479	30.9	46	66
35	32.8	224	490	42.3	44	63

2.9.3 Low temperature properties of Austenitic Ductile Iron

Highly alloyed Austenitic ductile irons are very ductile than ferritic DI as the former contains spheroidal graphite in austenitic matrix. A low temperature property mainly dependent on composition since it determines austenite stability and the presence of carbide [61]. Manganese, chromium and nickel strongly effects in increasing stability of austenite at low temperatures among which manganese is the most potent. Reduction in chromium content with increase in manganese to 2 % showed an improvement in ductility at room and low temperatures. Tensile strengths of stable austenitic cast irons increase at low temperature. Impact properties of austenitic flake graphite iron increase at low temperatures until transformation of martensite begins. But in case of austenitic nodular cast iron impact properties decreases although there was no transformation of martensite. Addition of copper up to 5 % may result in formation of a degenerate graphitic structure. The amount of carbide increases with increase in chromium content.

A. J. Rickard [64] investigated on development of special Ni Resist cast irons for low temperature use. Results showed that modifies Ni resist cat iron, in which manganese composition is raised from 2-4 % showed high toughness and ductility at temperatures down to -253˚ C.

2.9.4 ***General characteristics of Ni Resist Austenitic cast irons***

1. Corrosion resistance: these are specified for handling salt solutions, sea water, mild acids, alkaline and oil field liquids, both sweet and sour. These are characterised by uniform corrosion rather than by localised deterioration.

2. Wear resistance: Their galling resistance is excellent so are used as cylinder lines, bearing, pistons, wear rings and sleeves

3. Erosion resistance: slurries, wet streams and other fluids with entrained solids are substances which are extremely erosive to most metals. Ni resist alloys offer a combination of corrosion-erosion resistance in these environments [47].

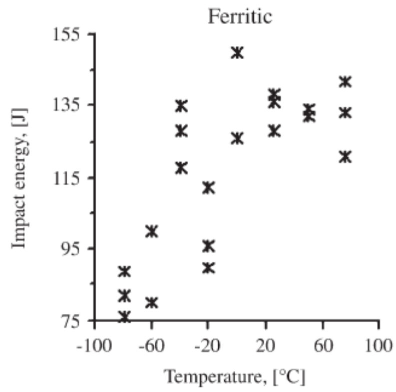
2.10 Impact toughness:

Impact energy is a measure of the work done to fracture a specimen. The specimen absorbs energy until it yields when the striker impacts the specimen. The specimen undergoes plastic deformation at its notch. Impact properties are influenced by the microstructure of specimen and testing temperatures. DBTT is exhibited by BCC metals, which become brittle at low temperature or at very high strain rates. FCC metals remain ductile at low temperature. Basically, in metals plastic deformation at room temperature occurs by dislocation motion. The flow stress of dislocation depends on atomic bonding, crystal structure and obstacles such as grain boundaries, solute atoms, precipitate particles and dislocations. If the flow stress of dislocation is high due to crack propagation, the material fails in a brittle manner. In FCC flow stress is not strongly dependent on temperature. So dislocation movement remains high even at low temperatures and material remains ductile. In bcc single crystals, the critical resolved shear stress is temperature dependent, particularly at low temperatures [36]. The temperature sensitivity of BCC crystals have been attributed to the presence of interstitials and temperature dependent peierls- nobarro force. However crack propagation stress is relatively independent of temperature. Hence the failure changes from plastic flow at high temperature to cleavage at low temperature. Ductile iron with annealed ferritic matrix exhibits the lowest ductile to brittle transition temperatures (DBTT) and highest upper shelf energy as the crystal structure of ferrite is BCC . In the range of 0-60˚C these irons have impact transition temperatures depending on composition, heat treatment and graphite properties. DI exhibits upper shelf energies in the range of 16-25J[6, 62]. As cast ferritic and pearlitic DI have higher transition temperatures and lower shelf energies. This is the reason why pearlitic grades are not recommended for low temperature properties where impact resistance is required due to their higher strengths with limited ductility and toughness [65-69]. The transition temperature of a material is raised if loading speeds are high or if a notch is present. For this reason, brittle fractures are more commonly observed during impact testing then there during normal tensile testing. It is important to appreciate, however, that brittle failure can occur under normal tensile loading if the conditions favours this mode of failure. A simplified explanation for this ductile–to–brittle transition behaviour, at higher temperatures, the stress required to cause plastic deformation is relatively low and failure occurs in a ductile manner, with considerable deformation, before the stress to trigger brittle failure by cleavage is exceeded. The stress required to cause plastic yielding increases rapidly as the temperature is decreased, and the stress required to produce brittle fracture may then be exceeded before plastic yielding can take place.

2.11 Recent trends in research on impact toughness of Ductile Iron

Yufu Sun et al.[6] Studies on how nickel effects impact and corrosion properties of alloyed ductile iron at low temperatures by varying Nickel percentages show that addition of Nickel at optimum levels showed better properties at low temperatures.

Gulcan Toktaş et.al [66] studies on effect of matrix on impact properties (Fig 2.14) resulted that the fracture modes of the ferritic, lower and upper ausferritic structures showed good impact properties. While the ferritic and the lower ausferritic structures displayed dimple mode of fracture whereas upper ausferritic showed brittle mode. The results are shown in fig.



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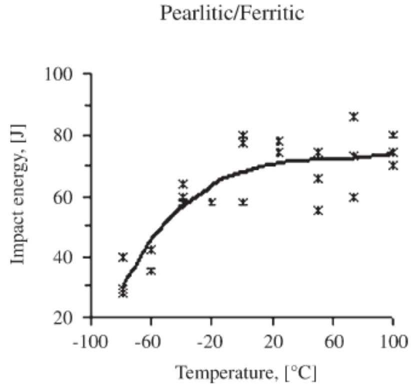

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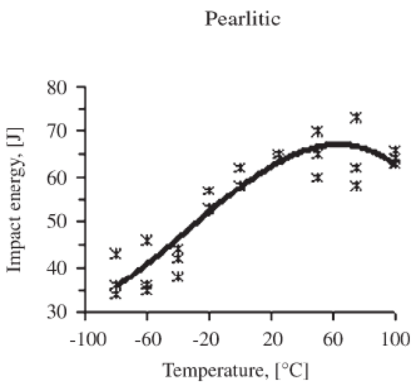

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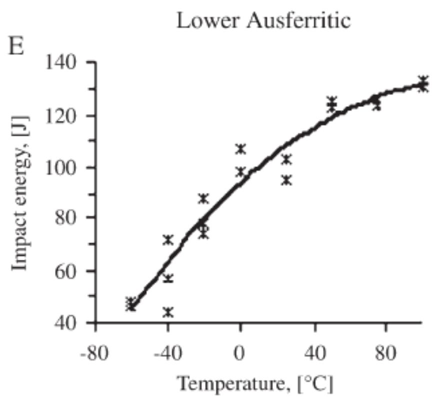

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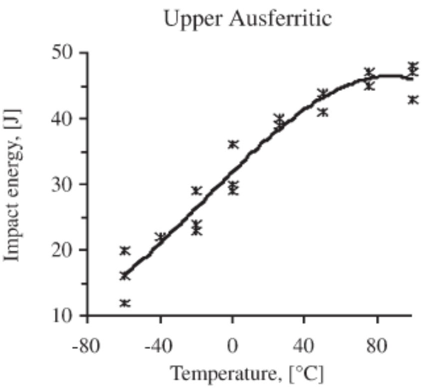

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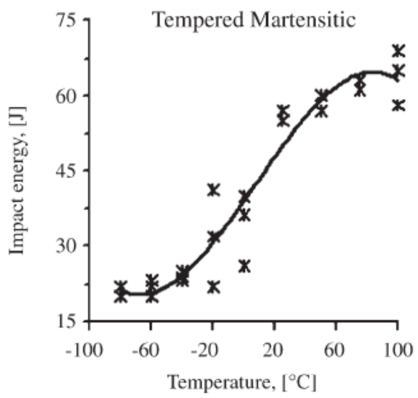


(f)

Fig 2.14: Impact energies (a) ferritic (b)ferritic/pearlitic (c)pearlitic (d)lower ausferritic (e) upper ausferritic(f) tempered martensitic matrices.

Ricardo A. Martinez [40] investigated the fracture surfaces of Ductile iron with associated failures by varying load bearings. Results show that cavity growth ends with coalescence of cavities giving fibrous aspect to the fracture surface characterized by the presence of dimples during the application of load and temperature. Depending on the nature of load and temperature this phenomenon is related to the ferritic matrices with certain differences. As test temperature drops the fracture mode at a slow monotonic load rate undergoes a gradual Ductile to Brittle Transition.

Cheng-Hsun Hsu et al. [43] studied about the mechanical properties of Ductile iron by adding 4% Co- Ni alloying elements. The results show the highest strength and hardness of 4% Ni alloyed iron due to the pearlitic content whereas ductility and toughness are not reached to the estimated levels.

Olivera Eric et al. [24] have studied about the fracture of alloyed Austempered Ductile iron. Results demonstrated that with increasing content of retained austenite up to maximum value increases impact energies and then minimum values are achieved with the decrease of retained austenite.

D. Rajnovic et al. [38] Studied about the transition temperature and fracture mode of as cast and austempered ductile iron. The results show that pearlitic matrix of ductile iron exhibited mostly brittle fracture at all temperatures whereas Austempered ductile iron gradually changed from ductile at upper shelf region, mixed mode at transition region to quasi cleavage fracture at lower shelf region.

The impact studies carried in the past are mainly focused towards the improvement of DI, ADI's and steels. However, a few attempts have so far carried out in determining the mechanical properties of austenitic ductile iron. This study has been undertaken to investigate the mechanical properties of austenitic ductile iron like tensile strength, hardness along with impact toughness at room temperature and sub zero temperatures

Chapter 3
Experimental Details

Experimental Details

This chapter illustrates about the work carried out in the present investigation. Different equipments/instruments that are essential to carry out the experiments are listed below with representing their use. Detailed cooling curves are also provided for different heat treatments adopted in the present work. The following methodology has been adopted:

3.1 Methodology

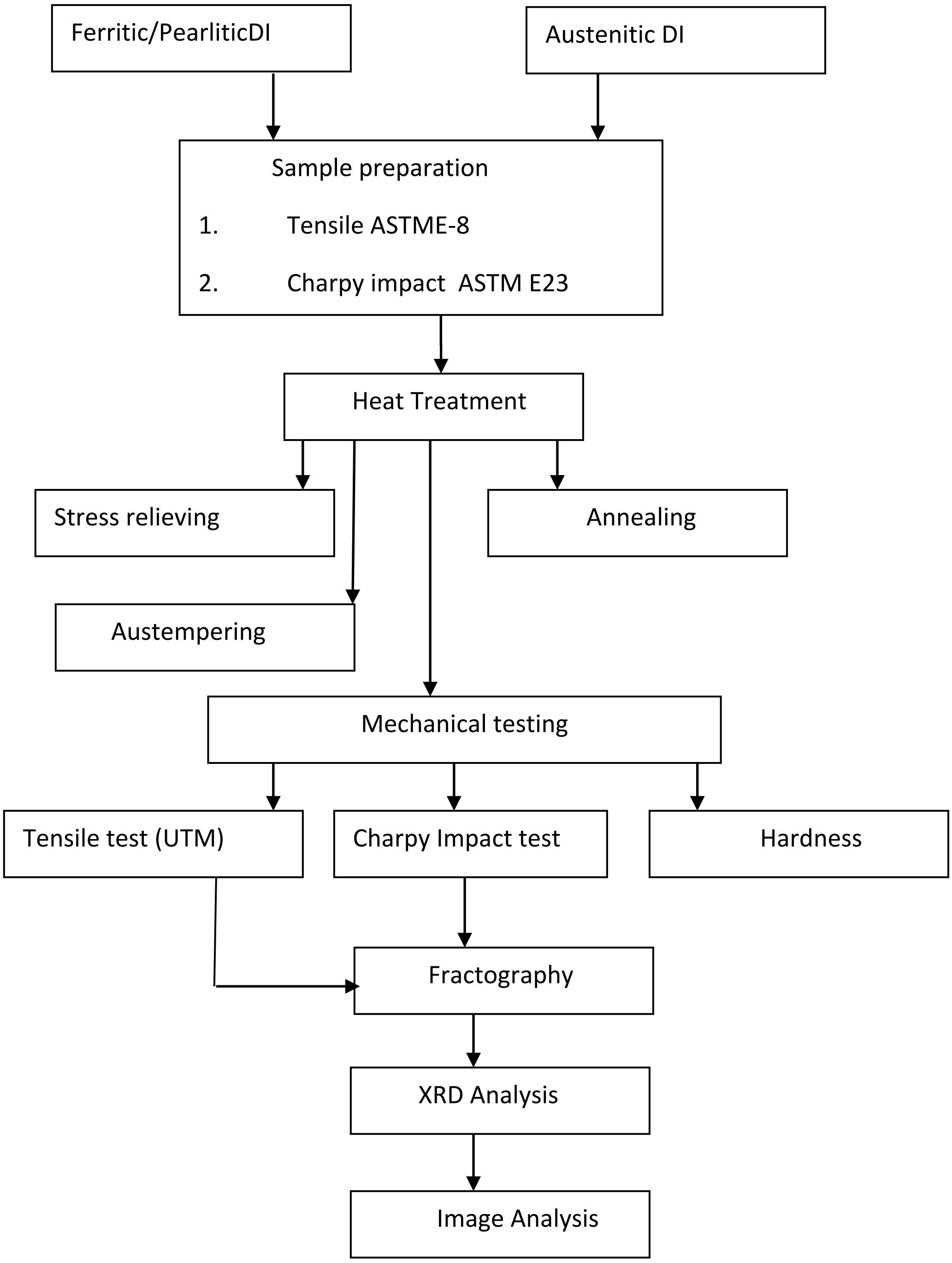


Fig 3.1: Flow chart for present investigation

3.2 Chemical Composition

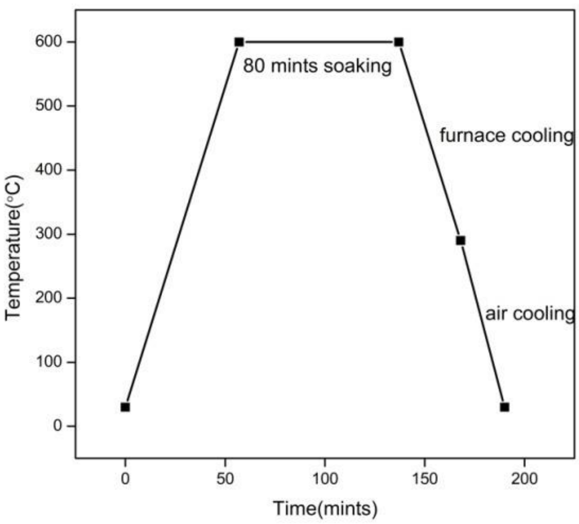
The chemical composition of 0.15% DI and Austenitic DI used in present work are presented in table 3.2

Table 3.1: Chemical composition of Ferritic/PearliticDuctile Iron and Austenitic Ductile Iron

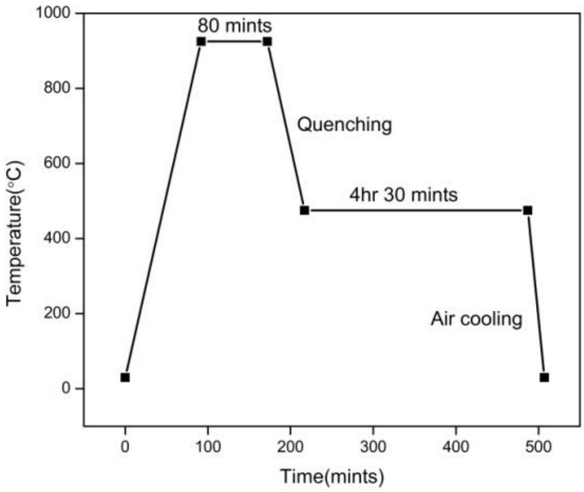
Element	C	Si	Mn	S	P	Cr	Ni	Mg	Cu	Fe
0.15%Ni DI	3.45	2.07	0.15	0.008	0.024	0.02	0.15	0.043	Nil	Rest
Austenitic DI	3.00	2.42	0.28	0.013	0.030	0.14	12.1	0.066	0.011	Rest

3.3 Heat Treatments

Two different heat treatments are done to the as cast material of Ferritic/Pearlitic DI. Stress relieving Fig 2 (a) and austempering Fig 2 (b). Stress relieving is done by heating the specimen to 600° C soaking there for 80 minutes, then cooled to 290° C, and finally air cooling to room temperature. Austempering is done by heating the specimen to 925°C soaking for 80 minutes and quenching inKNO_3+$NaNO_3$ bath (1:1 ratio) maintained at 475°C and holding there for 4hr 30 min and then air cooled to room temperature. Annealing treatment is done to the Austenitic DI by heating the specimen to 1000˚C soaking there for 80 minutes followed by air cooling.

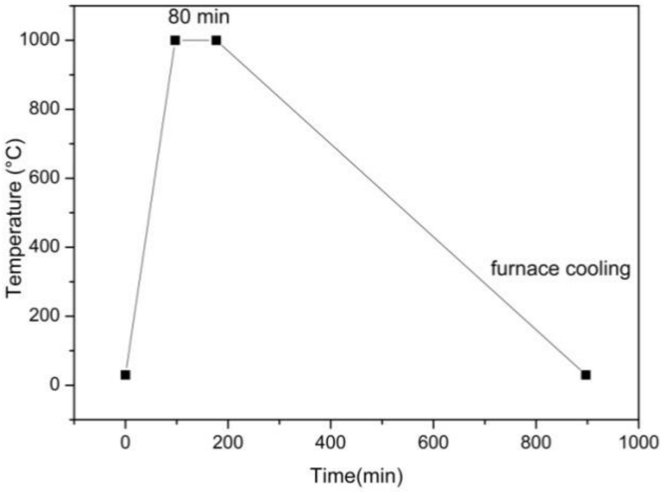


(a)



(b)

Fig 3.2: Cooling curves of (a) Stress relieving (b) Austempering of Ferritic/PearliticDuctile iron



3.3: Annealing of Austenitic Ductile iron

3.4 X- Ray Diffraction Analysis

The phases and crystal structures are detected by using X-ray diffraction analysis on RIGAKU ULTIMA 1V diffractometer filtered Cu-k alpha target (λ=0.1542nm) with scanning 7 degrees per minute in the range of 20°-110° with a step size of 0.02.The crystallographic planes of corresponding peaks are analyzed by using Xpert highscore and JCPDS software. From the crystallographic plane crystal structures are obtained. Volume fraction of retained austenite in ADI is calculated by direct comparison method using X Ray Diffraction data.

Fig 3.4: X-Ray Diffractometer

3.5 Optical microscopy

The samples were etched with 2%nital solution before viewing under microscope. Microstructures before and after heat treatments are observed under optical microscope. Morphological aspects such as nodularity and nodule count are determined before etching the sample and phase area fractions of respective matrices were determined after etching the sample following ASTM E2567-13a standard.

Fig 3.5: Metal power image analyser with optical microscope

3.6 Hardness test

Micro hardness is measured by using Vickers micro hardness tester with indentation load of 1kgf and dwell time 10 seconds. Before carrying out the hardness test the specimen is polished to have mirror polished surface to avoid rough surface. A minimum of 10 readings are taken for the estimation of average hardness values. Indenter used here is a square base diamond pyramid with the included angle between opposite faces of pyramid is 136˚. Schematic figure of indentation is shown in Fig 3.5

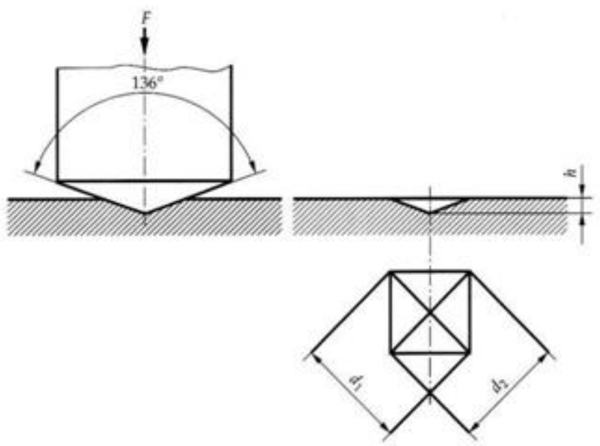


Fig 3.6: Schematic diagram of pyramid indentation

F= Test Force, in N

d_1 and d_2 = length of the diagonals of the indentation, in mm

h= depth of the indentation, in mm

the Vickers hardness is calculated by using the formula,

$$H_V = \frac{0.1889F}{L^2}$$

Where $L = \frac{d1+d2}{2}$

Fig 3.7: Vickers hardness tester

3.7 Tensile Test

After heat treating the samples, tensile test is carried out to all the Ferritic/Pearlitic DI and Austenitic DI. Tensile strength and % elongation are determined at room temperature by testing on universal testing machine (UTM) INSTRON-1995. Ultimate tensile strength and % elongation are calculated from the Load and Displacement plots that are obtained after testing under UTM. The dimensions of the test specimen are machined according to ASTM standards.

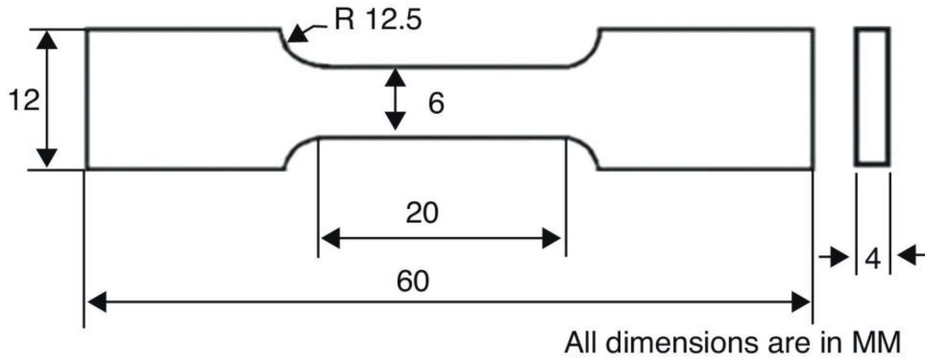


Fig 3.8: ASTM E-8, Flat sub size specimen

Fig 3.9: Universal testing machine

3.8 Impact test

Impact test is carried out for all the samples by using charpy impact tester. Charpy V-notch impact tests are conducted with test specimens whose dimensions are 55×10×10 mm^3 with depth of the notch as 2 mm and included angle is 45˚. Schematic figure of V notch specimen is show in Fig 3.9.The temperature for the Charpy V-notch impact tests are 0°C and -20℃. The Charpy Impact Test consists of striking a specimen with a hammer on a pendulum arm while the specimen is held securely at each end. The hammer strikes opposite the notch. The energy absorbed by the specimen is determined by precisely measuring the decrease in motion of the pendulum arm.

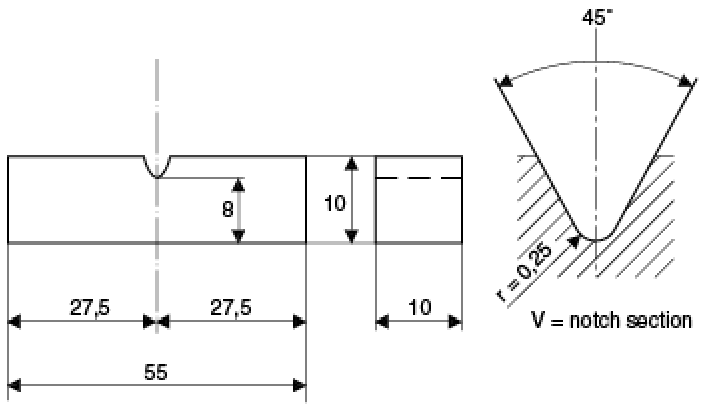


Fig 3.10: Schematic diagram of v-notch impact specimen with dimensions(mm)

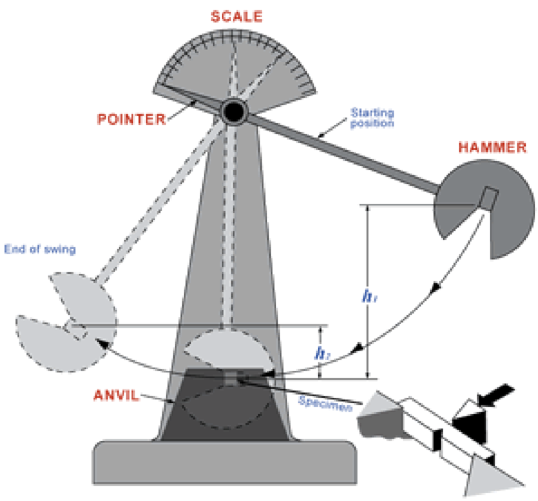


Fig 3.11: Charpy impact tester

3.9 Fractography

Fractographical studies are performed on the fractured surfaces to determine the type of fracture. The fracture surfaces after tensile and impact tests were observed under JEOL-JSM6480LY scanning electron microscope.

Fig 3.12: Scanning Electron Microscope

Chapter 4
Results and Discussion

Results and discussions

4.1 X -Ray Diffraction (XRD) Analysis

The X- Ray diffraction patterns are illustrated in Fig 4.1 for As Cast, Stress Relieved, and Austempered specimens of Ferritic/pearlitic Ductile Iron. It was observed that both as cast and stress relieved specimens showed BCC crystal structure justifying the presence of ferrite matrix phase. Austempered specimen showed (1 1 0), (2 1 1) planes suggesting the crystal structure as BCC and (2 0 0) (2 2 0) as FCC crystal structures justifying the presence of ferrite and austenite. The volume fraction of ferrite and retained austenite is calculated from Equation (1 &2)[33-34]. It consists of 80% ferrite and 20% retained austenite. This retained austenite contains 1.104% of carbon which was calculated from Equation (3)[35]. In Fig 4.2 patterns of as cast and austenitic ductile iron, all the planes determine the FCC crystal structure reflections which suggest the presence of austenitic phase.

$\frac{I\gamma}{I\alpha} = \frac{R\gamma X\gamma}{R\alpha X\alpha}$- ------------ Equation (1)

$X_{\alpha}+X_{\gamma}= 1$ --------------Equation (2)

$a_{\gamma} = 0.3548+0.0044\, C_{\gamma}$-------------Equation (3)

I = integrated intensity per unit length of diffracted line.

R= theoretical intensity

X = volume fraction.

α=ferrite, γ= austenite

a_{γ} = lattice parameter of austenite peaks

C_{γ}= carbon percentage in austenite.

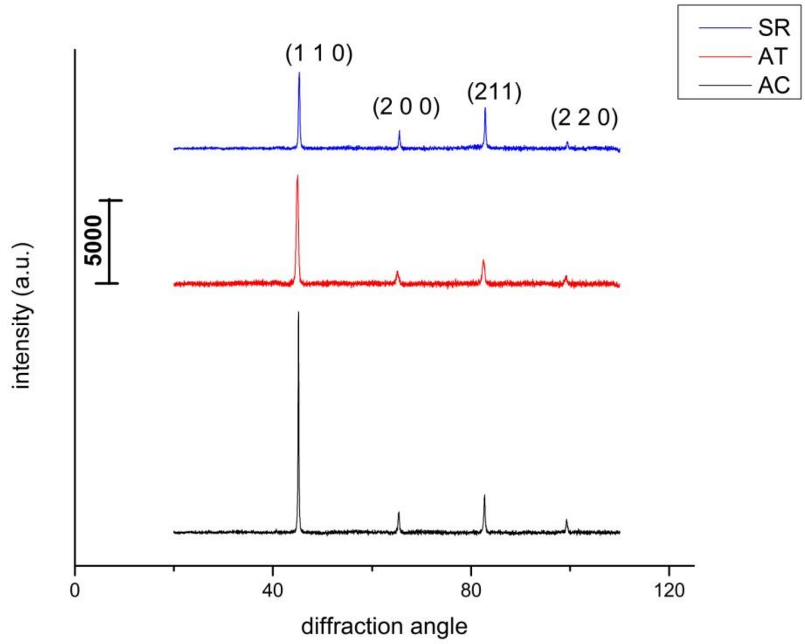


Fig 4.1: XRD Plot of Ferritic/Pearlitic Ductile iron

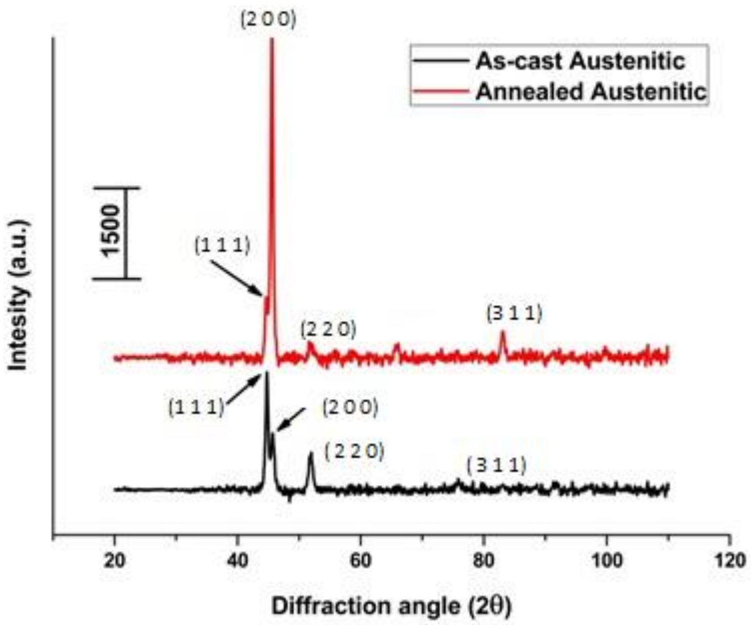


Fig 4.2: XRD Plot of Austenitic Ductile iron

4.2 Morphological studies

The microstructure of as cast Ferritic/Pearlitic DI (Fig.4.3 (a)), consists of 16.32% nodular graphite embedded within 81.51% ferrite by area fraction. The diameter of graphite nodules ranges from 4-25mm with 98% nodularity in as cast, 86% in stress relieving and 95% in austempered DI. After stress relieving treatment the microstructure (Fig 4.3 (b)), remains same as in as cast condition i.e. graphite nodules embedded in ferritic matrix. The nodule count influences the ferrite/pearlitic content of matrix and its mechanical properties [31,44].The nodule count and area fractions of respective specimens were shown in Table 4.1. Increase in nodule count resulted in higher elongations, lower hardness and ultimate tensile strengths. The austempered microstructure consists of 4.67% graphite with 93.51% upper bainite by area fraction. This retained austenite combined with bainitic ferrite is responsible for certain mechanical properties like ductility and impact values due to the excess carbon that redistributed into the austenite [32]. The microstructure in Fig4.3(c) consists of spheroidal graphite embedded in upper bainitic matrix as the quenching temperature is 475°C. The microstructure of as cast austenitic DI (Fig 4.4(a)) consists of 12%nodular graphite embedded within 88% austenitic matrix. Whereas annealed specimen (Fig 4.4 (b)) consists of 18% graphite embedded within 82% Austenitic matrix by area fraction. The diameter of nodules ranges from 4-22 mm in each case with around 96% nodularity.

Table 4.1: Morphological quantification

	specimens	Nodule count	Nodularity (%)	Graphite area fraction (%)	Ferrite area fraction (%)	Bainite area fraction (%)	Ferrite volume fraction (%)	Austenite volume fraction (%)
Ferritic/PearliticDI	As cast	86	98	16.32	81.51	--------	--------	--------
	Stress relieved	60	83	16.28	82.18	--------	--------	--------
	Austempered	57	95	6.48	--------	93.51	80	20
Austenitic DI	As cast	46	96	12	--------	--------	--------	88
	Annealed	36	96	18	--------	--------	--------	82

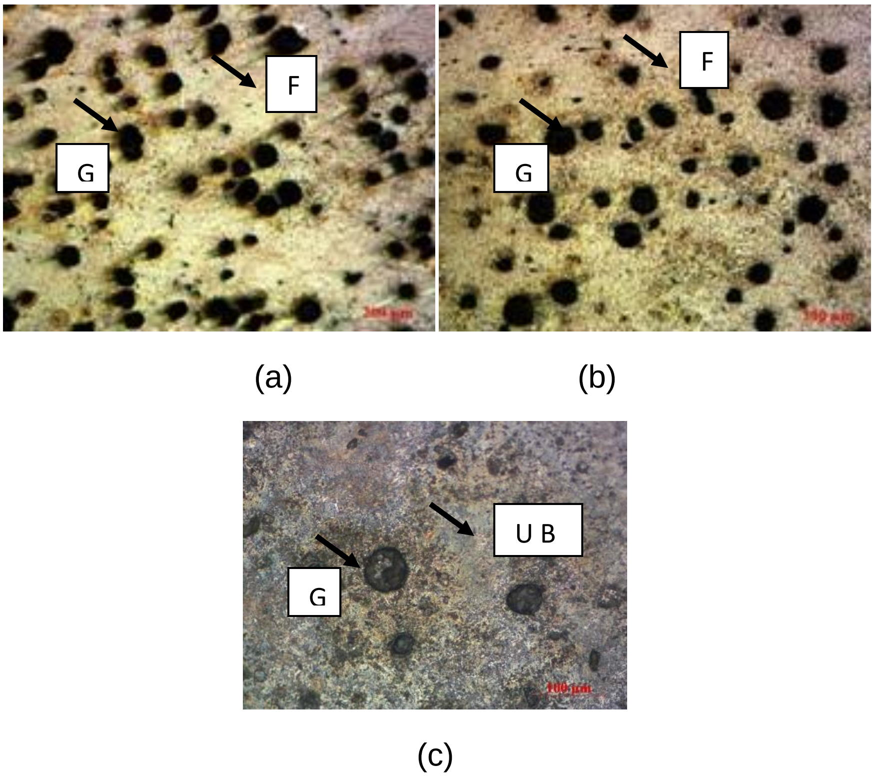


Fig 4.3: Microstructures of Ferritic/Pearlitic DI (a) As cast (b) Stress Relieved (c) Austempered

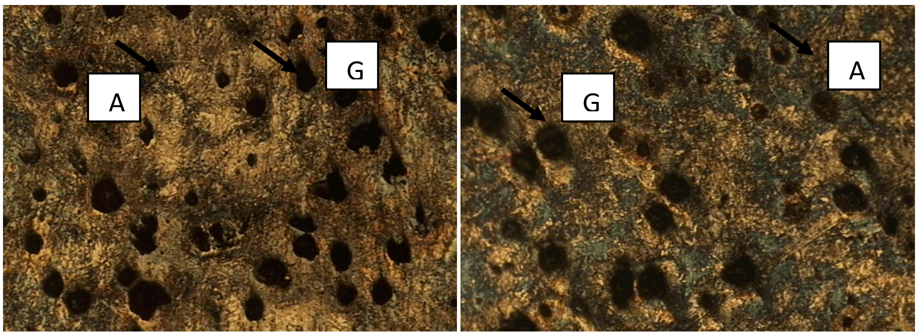


Fig 4.4: Microstructures of Austenitic DI (a) As cast (b) Annealed

4.3 Mechanical properties

4.3.1 Hardness

From Fig 4.5, the hardness of as cast and stress relieved Ferritic/Pearlitic DI are low when compared to austempered ductile iron due to ferritic matrix in former case [9-14]. The hardness of austempered was increased due to the presence of high carbon retained austenite (upper bainitic matrix) that formed during austempering treatment [43]. As annealing results in reliving internal stresses and acquiring coarser grain structure, the annealed austenitic DI showed lower hardness values when compared to as cast samples. Austenitic samples showed lower hardness values as it contains 80% uniform austenitic matrix when compared to the austempered ductile iron which contains only 20% of austenitic in upper bainitic matrix.

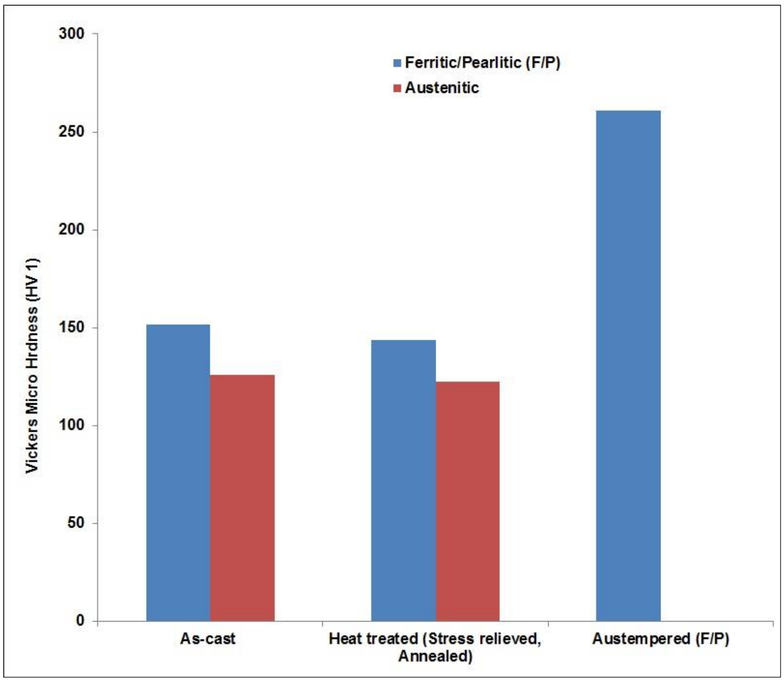


Fig 4.5: Hardness

4.3.2 Tensile strength

Results from Table.4.2, shows that tensile strength of austempered specimen has higher values than as-cast and stress relieved Ferritic/Pearlitic DI specimens, with 10.33% elongation due to the higher hardness values of upper bainitic matrix. Whereas stress relieved and as cast specimens showed variations in tensile strength with 23% & 19% elongations at break respectively due to the ferritic matrix. Improvement in elongations is due to the relief of residual stresses after stress relieving treatment. Annealing of austenitic ductile iron resulted in decrease in tensile strength with 26 % elongation whereas as cast sample showed higher strengths with 23 % elongation. Minimization of residual stresses in the matrix structure and coarser grain size of the matrix resulted higher elongations in annealed specimens with lower tensile strength [13, 14, 22, 69]

Table 4.2: Tensile strength

	Sample	Tensile strength(Mpa)	% elongation
Ferritic/PearliticDI	As Cast	342.0	19
	Stress relieved	331.16	23
	Austempered	727.4	10.330
Austenitic DI	As Cast	310	23.00
	Annealed	290	26.00

4.3.3 Impact toughness:

When an impact load is applied to a DI, separations are primarily caused along the interfaces between graphite nodules and matrices immediately after deformation exceeds elastic limit. But the stress may not be relaxed by such separations and so those stresses are induced into the matrix region. This resulted in the fracture on the slip bands. As a result the cracks nucleated in graphite matrix boundaries are connected to interface separations and the material is fractured finally. In the present study, austempered samples exhibited lowest impact toughness when compared to the as cast and stress relieved Ferritic/PearliticDI. It is evident from the figure that the energy absorbed by the material depends on the matrix [22].Due to higher strength and hardness of upper bainitic matrix, austempered specimen has absorbed less amount of energy during fracture. In case of austenitic ductile iron, the annealed specimens exhibited higher impact energies when compared to the as cast specimens due to the fact that higher the elongations, higher will be the absorption of energy during fracture. Impact test at low temperatures (-20˚C) showed that there is a decrease in energy values in all Ferritic/PearliticDuctile iron samples when compared to the values at room temperature. Results showed that there is no change in impact energies of Austenitic ductile iron samples at low temperatures. Table 4.3 shows the differences of energies that are obtained during impact test at both room temperature and -20˚C.

Table 4.3: Impact toughness

	Sample name	Impact energy (J)	
		RT	-20˚C
Ferritic/PearliticDI	As Cast	16	14
	Stress relieved	18	17
	Austempered	14	10
Austenitic DI	As Cast	16	16
	Annealed	19	19

4.4 Fractographic study

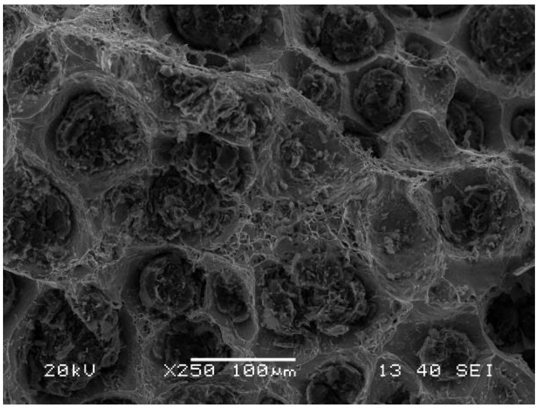
After carrying out the tensile and impact tests the fracture surfaces are viewed under scanning electron microscope to examine the mechanism of fracture.

4.4.1. Impact specimens

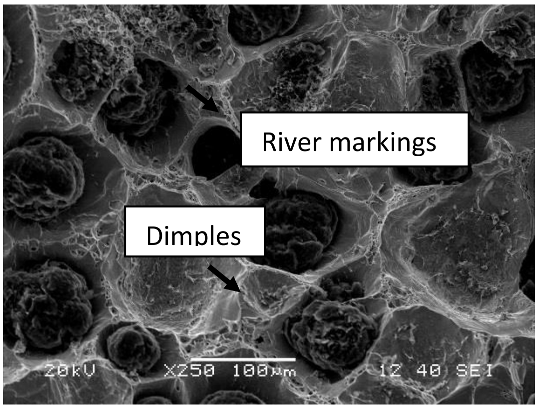
Impact test was carried out at room temperature and -20˚C.

4.4.1.1 At room temperature

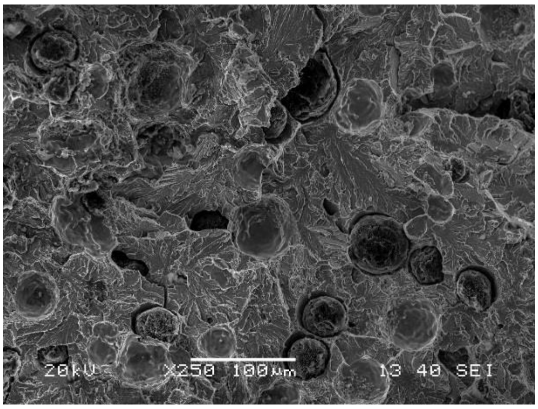
In Fig 4.6(a), the fracture surface at room temperature clearly shows the presence of dimples, a smaller size and shallower depth corresponding to micro voids that initiate crack formation. Dimple rupture is characterized by cup like depressions which represents ductile fracture. In Fig.4.6 (b), the stress relieved fracture surface shows the presence of dimples with river patterns justifying mixed mode of fracture i.e. combination of both ductile and brittle fracture. But in Fig 4.6(c), fracture surface consists of river markings which are low energy stress paths caused by crack moving through the crystal along parallel planes which form series of plateaus and connecting ledges. It also consists of dimples on its surface. These dimples and river markings justifies the fracture as quasi cleavage fracture [37, 38, 40-45]. The fracture occurs due to higher hardness accompanied with higher strength. Fracture surface of as cast austenitic ductile iron (Fig 4.7(c)) shows the existence of dimples with river markings which justifies the fracture as quasi cleavage mode. Coming to annealed austenitic ductile iron (Fig 4.7(d)) the surface showed dimple rupture and little amount of river markings when compared to the as cast specimens. This is due to the improvement in ductility after annealing treatment to this material.



(a)

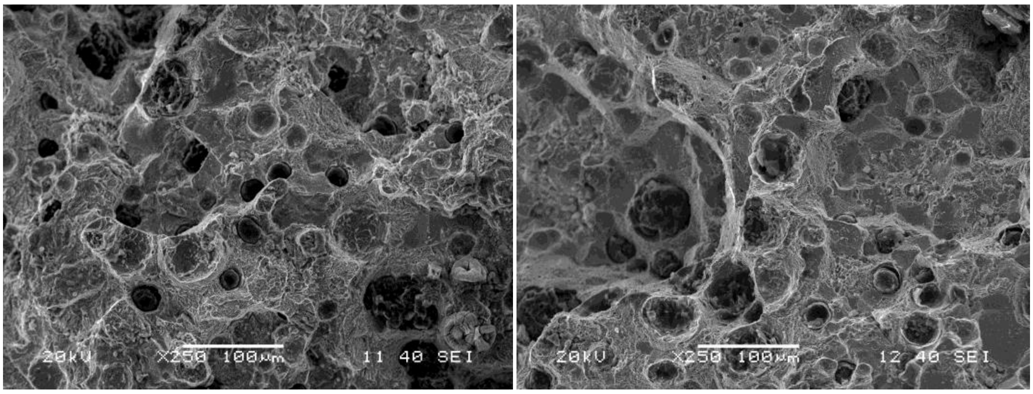


(b)



(c)

Fig 4.6: Microstructure at room temperature (a) As cast (b) stress relieved (c) Austempered Ferritic/PearliticDuctile iron

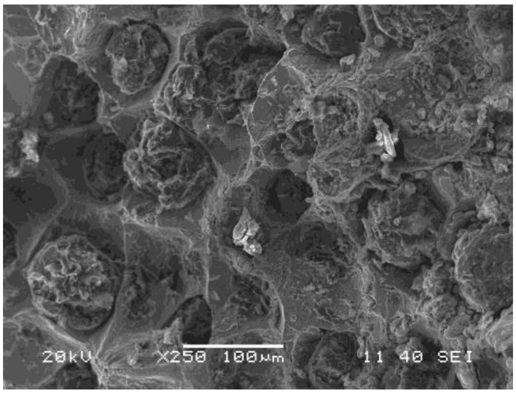


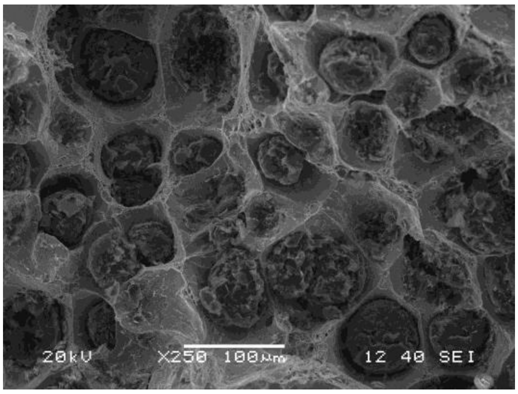
(c) (d)

Fig 4.7: Microstructure at room temperature (c) As cast (d) Annealed Austenitic Ductile Iron

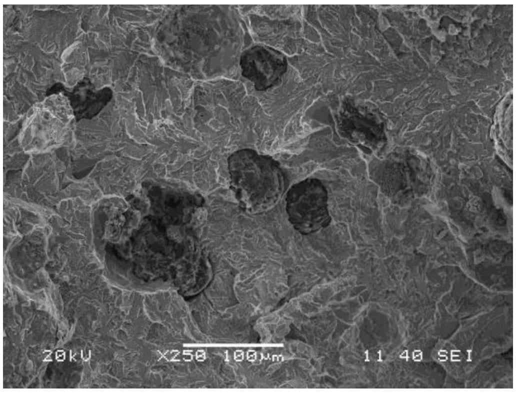
4.4.1.2 At -20˚C

Fig 4.8 (a&b) the fracture surfaces consists of a combination of river markings and dimples which signifies the fracture as mixes mode. (quasi cleavage). Austempered specimen(Fig 4.8(c)) showed complete faceted structure proving the type of fracture as brittle. In case of austenitic ductile iron as cast(Fig 4.9(c)) and annealed samples(Fig 4.9(d)) showed quasi cleavage fracture that can be justified by the presence of both the flat faceted structure and spherical dimples in the matrix. This type of fracture is due to the austenitic matrix which is the softest phase in the iron carbide diagram. The fracture surfaces of Ferritic/PearliticDuctile iron observed to be undergone slight brittleness at low temperature due to the ferritic matrix which is BCC crystal strucure. Whereas fracture surfaces of Austenitic ductile iron does not show any difference sue to its austenitic matrix whose crystal structure is FCC. FCC metals do not show ductile to brittle transition at low temperatures as the flow stress is independent of temperature in FCC metals[38,64].



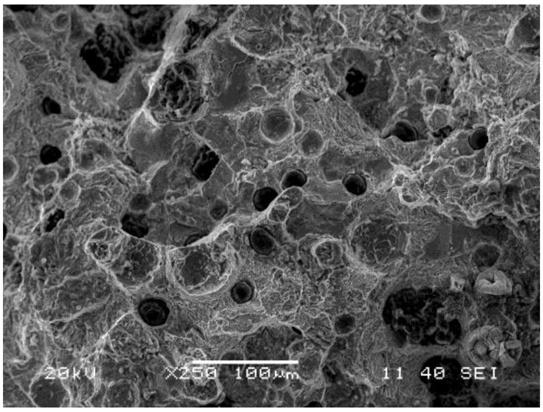


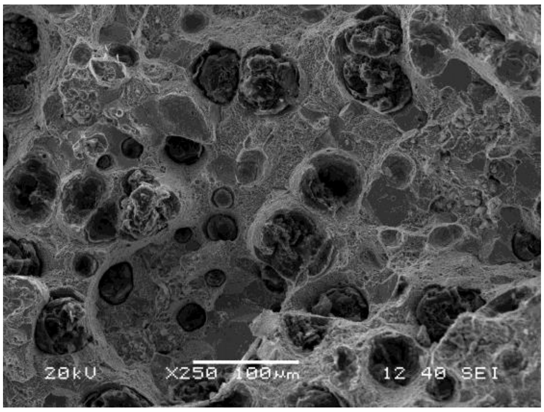
(a) (b)



(c)

Fig 4.8: Microstructures at -20˚C (a) As cast (b) stress relieved (c) Austempered Ferritic/PearliticDuctile iron



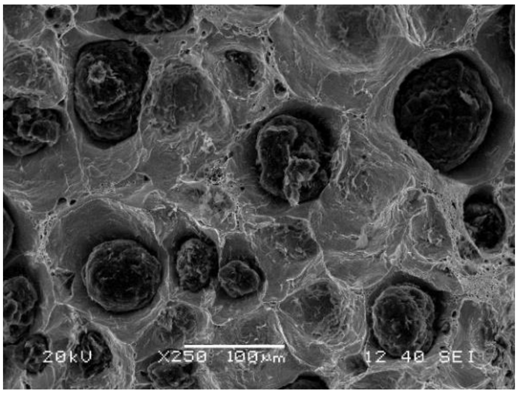


(d) (e)

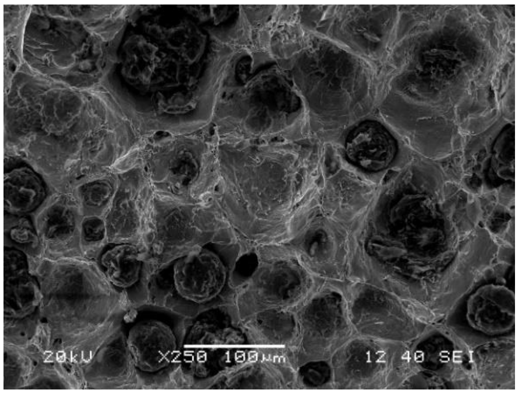
Fig 4.9: Microstructures at -20˚C (d) As cast (e) Annealed Austenitic Ductile Iron

4.4.2. Tensile specimens

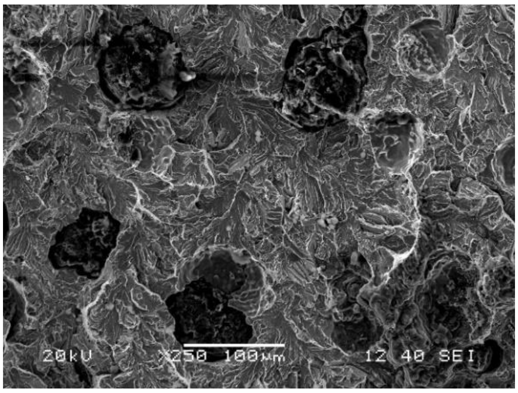
In Fig4.10 (a & b) the fracture surfaces of as cast and stress relieved Ferritic/PearliticDuctile iron that consists of spherical dimples which signifies the mode of fracture is ductile. Fig 4.10(c) ADI fracture surface showed faceted structure because cleavage planes in grains have different orientation [29]. This flat facet is a characteristic feature of cleavage fracture. Fig 4.11(a&b) shows the fracture surfaces of as cast and annealed austenitic DI. Both the surfaces have river markings i.e. flat faceted structure along with spherical dimples signifies that the fracture as a quasi cleavage mode.



(a)

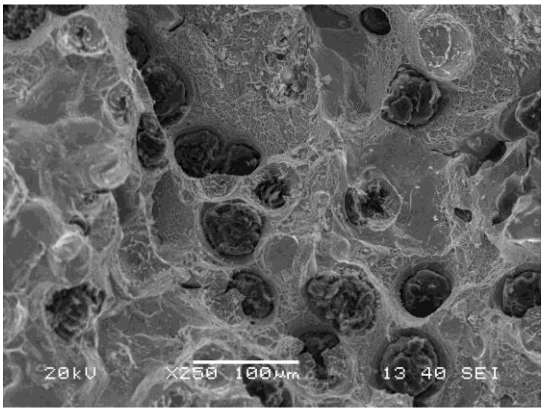


(b)

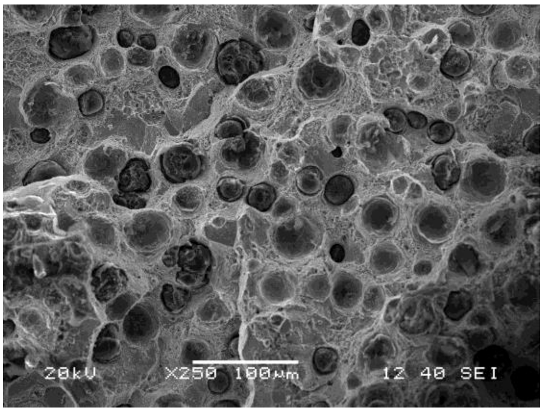


(c)

Fig 4.10: Microstructures of (a) As cast (b) stress relieved (c) Austempered Ferritic/PearliticDuctile iron



(d)



(e)

Fig 4.11: Microstructures of (d) As cast (e) Annealed Austenitic Ductile Iron

Conclusions

Conclusions:

The present work reports the results of “Comparison of mechanical properties of Austenitic Ductile Iron withFerritic/Pearlitic Ductile Iron”. The following results are drawn from investigation.

1. The microstructure of stress relieved and Austempered Ductile Iron has spheroidal graphite embedded in the ferritic matrix and upper bainitic matrix respectively. Whereas Austenitic Ductile iron consists of nodular graphite embedded in the uniform austenitic matrix.
2. The tensile strength and hardness of Austenitic ductile iron are lower when compared to the stress relived Ferritic/Pearlitic Ductile and austempered Ductile Iron.
3. As cast and stress relieved Ferritic/Pearlitic Ductile Iron showed higher impact energies with quasi cleavage mode of fracture when compared to austempered Ductile Iron. In case of Austenitic Ductile iron, impact energies are higher than as cast and stress relieved Ferritic/Pearlitic Ductile Iron and fractured by quasi cleavage mode.
4. At -20˚C Austenitic ductile iron doesn’t show ductile to brittle transition temperatures and no change in impact energies is observed. Whereas impact values of Ferritic/Pearlitic Ductile Iron are decreased and austempered Ductile showed brittle fracture.
5. As a result, Austempered Ductile Iron performs better in uniaxial tensile conditions. And as cast, stress relieved Ferritic/Pearlitic Ductile Iron has better impact properties. Austenitic ductile iron showed enhanced impact properties with quasi cleavage mode of fracture at both room temperatures and low temperatures when compared to Ferritic/Pearlitic Ductile Iron.

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Dissemination

- Institute of Physics Journal IOP Conference Series: Material Science and Engineering, M Salim, S Shama[1], Y H Mozumder, R K Behera, Sindhoora L P, A Pattanaik, S C Mishra and S Sen; Adhesive Wear Behavior of Heat Treated Spheroidal Graphite Cast Iron
- Institute of Physics Journal IOP Conference Series: Material Science and Engineering, V K Jha, Y H Mozumder, S Shama, R K Behera[1], A Pattaniak, Sindhoora L P, S C Mishra and S Sen; Dry sliding wear system response of ferritic and tempered martensitic ductile iron

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